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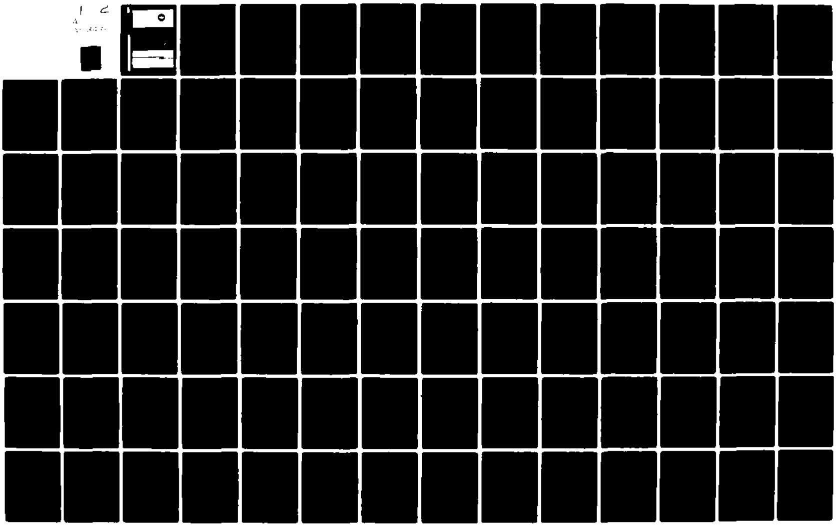

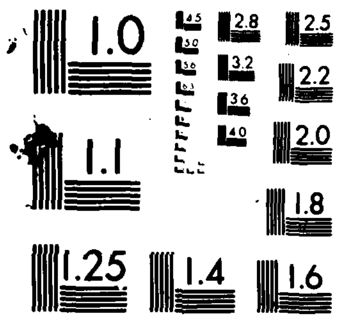

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THE PENNSYLVANIA STATE UNIVERSITY

GREAT LAKES SIMULATION STUDIES
Volume 2

LAKE ERIE-LAKE ONTARIO NAVIGATION: A SIMULATION STUDY OF ALTERNATIVE SUBSYSTEMS

By

Joseph L. Carroll
Department of Business Logistics

Srikanth Rao
Department of Management

Interim Report
Contract No. DACW23-72-C-0066

January 1973

PENNSYLVANIA TRANSPORTATION
AND TRAFFIC SAFETY CENTER

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In developing a computer model for the simulation of the Great Lakes and St. Lawrence Seaway navigation system, this report studies the input data base and calibration for single and multiple channel navigation for the Welland Canal with some remarks on the proposed Niagara Canal.

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Lake Erie-Lake Ontario Navigation:

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U.S. Army Corps of Engineers

North Central Division

Pennsylvania Transportation and Traffic Safety Center

The Pennsylvania State University

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ABSTRACT

This report presents the findings and conclusions of a computer simulation study of the Welland Canal and proposed alternatives to the Welland. The objective of this study was to establish the limits of service for alternative structural and nonstructural improvements in terms of delay and transit time. Waterborne transport demand through the year 2030 was considered in the analysis, demand being represented by two factors, traffic density and fleet composition. The results of the study were portrayed as a series of transit time response curves for each configuration, plotted as a function of the transport demand.

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FOREWORD

The work described in this interim report was performed by the Pennsylvania Transportation and Traffic Safety Center (PTTSC) at The Pennsylvania State University for the U.S. Army Corps of Engineers, North Central Division, under contract number DACW-23-72-C-0066. The contract period is from 1 July 1972 to 31 June 1973.

The effort reported herein represents a continuation of work at PTTSC in the general area of waterway systems planning and analysis. An earlier interim report entitled Great Lakes Simulation Studies, Volume 1--NETSIM: A General Network Simulator documented the development of a simulation model for multiple channel deep draft navigation studies. The present report applies this model to the Lake Erie-Lake Ontario navigation subsystem.

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The authors would like to take this opportunity to thank each member of the project team listed in the Foreword for their efforts in bringing this study to a successful conclusion. Thanks are also due to Mrs. Ru-Fen Chow of PTTSC for her editorial assistance.

The opinions, findings, and conclusions expressed in this publication are those of the authors, and not necessarily those of the Corps of Engineers nor The Pennsylvania State University.

I. INTRODUCTION

This report is part of a three-phased study commissioned by the U.S. Corps of Engineers to assist them in their appraisal of the capacity of the Great Lakes navigation system with focus on the structural and nonstructural improvements that may be postulated by the increasing waterway demand. The first two tasks were concerned with the capacity of the existing Welland Canal and the potential need for a parallel Lake Erie-Lake Ontario (LE-LO) Canal via the Niagara River. The final task was formulated to assist the Corps of Engineers with additional Great Lakes System Studies including St. Lawrence River Navigation, Great Lakes Season Extension, and Sault Ste Marie (Sabin) locks. These tasks may be summarized as follows:

1. to develop a LE-LO Navigation Simulation model,
2. to apply the model to simulation studies of the Welland Canal and proposed alternatives to the Welland,
3. to revise the initial simulation model so as to include the capabilities needed for comprehensive Great Lakes-St. Lawrence System simulations.

Task 1, the development of the simulation model, has been documented previously (1).[1] The present report presents the findings of Task 2, viz., the application of this model to the Welland-Niagara[2] complex.

A. TASK 2: LE-LO - WELLAND CANAL STUDIES

This phase of the study involves four major subtasks, as follows:

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[1]Numbers in parentheses refer to the list of References.

[2]The terms "Niagara Canal" and "LE-LO Canal" are used interchangeably in this report.

1. to establish the expected limits of service of the existing Welland Canal,
2. to establish the expected incremental increase in service potential of the existing Welland Canal under assumptions of improved locking procedures and an improved traffic control system,
3. to determine the expected performance of a combined Welland-Niagara system with configuration alternatives of four, five and six locks in series in the Niagara Canal in combination with the existing Welland Canal,
4. to examine the expected performance of a replacement for the Welland Canal consisting of a series of four super locks plus a guard lock towards the mouth of Lake Erie.

These configurations were subjected to current and anticipated levels of traffic, fleet composition, ship size, and operating procedures. The primary measure of system performance was system transit time. This variable reflects both the service levels provided by system facilities and any delays that occur due to congestion. In addition, measures of lock utilization, lock processing time, and time spent in queues were taken so that the system response could be stated in terms of delays due to congestion and lock utilization. However, no analysis of the effects of delays and system congestion upon demand was undertaken. Hence, the emphasis of the study was placed upon determining what configurations of navigation facilities are required to meet the prospective transportation demand and enable the network to function effectively as a system.

B. SYSTEM DESIGN ALTERNATIVES

Simulation of the existing Welland Canal established the calibration values for the model's parameters. Recent traffic data for the Welland Canal were used to establish state-dependent relationships between vessel transit time and the number of ships in the canal. The canal was simulated using input data representative of the conditions corresponding to those for which the traffic data were compiled. The capacity of the existing canal was established by subjecting it to waterway transport demand through the year 2030.

It has been reported that improvements in locking operations and the installation of a traffic control system in the Welland Canal have led to an increase greater than 33 percent in the potential number of lockages per day (2). The study cited also states that on the average, 1 minute saved per lock cycle[3] saves 1 hour in round-trip transit time for the vessels. An earlier report stated that a lock cycle time of 70 minutes might eventually be achieved (3). The conclusions reached in these two reports suggest that the already improved locking time might be further reduced by an additional 2 minutes resulting in a further improvement in round-trip transit time on the order of 2 hours.

The effects of nonstructural improvements in the Welland Canal can be inferred under the assumption that the optimization of vessel scheduling and locking procedures can, in fact, lead to improvements in vessel transit time on the order of those stated above. Simulation runs for future time

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[3] A lock cycle is the time needed for a lock to move one vessel down and one vessel up. This includes all the ship movements and lock operation from the time a boat is instructed to enter a lock to the time when the lock is ready to receive the next lockage in the same direction.

periods using inputs revised to incorporate these efficiencies were made in order to ascertain the capacity of an "improved" Welland Canal.

For the purposes of this study, the Welland Canal was modeled as a set of six entities, corresponding with the traffic data that were compiled, where the operations within each entity were inferred rather than specifically modeled. Transit time through the system depended on the number of ships in the canal and was calibrated on the basis of empirical data. The effects of additional nonstructural improvements to the canal were determined by simulation experiments as described above.

Four different structural alternatives for the Welland Canal were studied. Three of these alternatives consisted of two parallel channels in a combined Welland-Niagara system. The performance of this system was measured for configurations of four, five, and six locks in series in the Niagara Canal in combination with the existing eight-lock Welland. The simulation used transit time data representative of the future improved operations at the Welland and performance data for the Niagara based on specifications for locks and reaches provided by the Corps.

The fourth structural configuration involves a unilateral Canadian alternative to the Welland where the existing system would be replaced by a series of five locks[4] of greater lift and 1200' x 100' dimensions. This configuration was simulated as a single channel using performance data for locks and reaches from specifications provided by the Corps.

C. METHODOLOGY

The basic methodology for the Welland-Canal simulation experiments entailed the division of traffic between parallel facilities. This factor

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[4] Includes a guard lock.

dictated that a channel assignment mechanism be incorporated in the modeling system. As a result of discussions with the Corps, the groundwork for this system was laid in a previous study conducted at PTTSC (4). The following model specification was formulated:

1. Canal Operating Rule: all ships may use either existing or new facilities when physically possible; ships too large to use the existing locks must be assigned to the large new locks.
2. Lock Operating Rules: ships queuing on both sides of a lock should be serviced alternatively. A recycle "lookahead" capability should be included such that, there being no queues at a lock, the lock water level should be adjusted to accept the second of two ships traveling in the same direction, prior to its arrival at the lock, time permitting.
3. Reach Operating Rule: ships should be allowed to catch up with, or fall further behind a preceding ship but should not be allowed to pass a preceding ship in a canal reach.
4. Assignment Decision Rule: ships should be assigned between parallel facilities on the basis of the least expected transit time.

The model formulation has been extensively documented in the Task 1 report but a brief mention of the assignment decision mechanism is made here since it has a significant bearing on the methodology of the simulation experiments.

The assignment decision involves the simulation of each parallel branch separately, using a special option embedded in the simulation model to produce an "experience data base" (EDB). These experience data bases are then statistically analyzed to select the most significant variables and to establish coefficient values for use in a set of transit time

estimating functions for each branch. The coefficient values and variable identities for use in each branch estimating equation are specified by the user. With these calibrated functions available, simulation of the system of parallel canals can be performed. When a ship arrives at a channel choice point, the channel assignment is based on the least expected transit time.

This empirical approach was adopted because it was found that an analytical approach to the determination of expected transit time through a multiple lock and reach canal was extremely complex and was intractable. It is, therefore, postulated that a statistical relationship should exist between the conditions existing in a canal when a ship arrives at the assignment decision point and the time that will be required to subsequently travel through that canal. By performing a simulation (called an EDB run) of a given channel configuration (i.e., a specific canal branch), it is possible to develop an experience data base which includes prior canal conditions for each ship arrival and subsequent ship transit time. This data base may then be analyzed, using a standard statistical program, to establish the required relationships between expected transit time and canal conditions. Separate relationships for each of the Welland-Niagara configurations, differentiated by direction of travel, have been developed and are presented in Appendix B.

Thus, the EDB concept requiring preliminary simulation runs for the formulation of the expected transit time functions constitutes the first phase of the methodology. The actual simulation of the network configurations, using these expected transit time functions, for various input factors through different levels of transport demand forms the second phase. An actual simulation (called an EVENT LOG run) generates a log of

each event occurrence during simulation, and this event log is usually placed on an external output device such as a magnetic tape for permanent storage. It is this event log which is used during the third phase of the methodology.

Because of the complexity and sheer volume of the simulation model's logic structures, the burden of statistical evaluation was shifted to a post-simulation phase. Thus, the third phase consists of an event log post-processor which utilizes the event log generated during the second phase to summarize significant statistical data. The task of this event log processor is conceptually simple since it merely reads in the event log as input data and translates it into periodic (thereby providing intermediate snapshots) statistical summaries. The processor, however, also includes options for determining such simulation specifics as transient time and autocorrelation in data.

The distinction between "transient state" and "steady state" is extremely relevant for simulation studies. A transient state is defined as a condition in which operating characteristics of a system are changing with time in irregular fashion; and, conversely, a steady state means an environment in which system operating characteristics are not time varying. In the simulation context, a transient state usually exists at the start of a simulation run when the system is in some initial state. During the course of the simulation, the system eventually reaches a steady state as it accepts more entities, although under high utilization the system may depart from steady state.

Thus, the amount of simulation time required to reach this steady state (called warm-up time) is of critical importance to the analyst as he will normally want to make decisions based only on steady state performance

measures. The warm-up time may be determined in a number of ways (5). The event log processor uses a procedure that examines the behavior of delays at locks through spectral analysis.

The spectral analysis methodology was originally necessitated by the presence of autocorrelation in simulation data. That is, in most simulations generating time series data there is a certain degree of dependence on past events which violates a common statistical requirement that the data be independent. A spectral analysis approach, however, can be used in such cases to measure autocorrelation and take it into account in the subsequent analysis. This approach has been documented elsewhere (6); hence, no description is given here. The use of this approach in the Welland-Niagara studies led to the choice of 5000 minutes as the warm-up time and 30,000 minutes as the total simulation time.

D. ASSUMPTIONS

All simulation experiments were conducted under certain assumptions agreed to between PTTSC and the Corps of Engineers. These assumptions are:

1. The system never breaks down.
2. All locks operate under the "SOQA" (Serve Opposing Queues Alternatively) rule, where ships queuing on both sides of a lock will be served alternately, reverting to "First Come First Served" only when one queue becomes empty.
3. The channel-choice decision rule for parallel branches is based on least expected transit time.
4. There are no double, tandem or combination lockages.
5. There is no priority service given to any ship.
6. Time of day does not affect traffic levels (nor day of week, nor month of season).

7. Locks operate 24 hours per day, 7 days per week.
8. There will be no passing in any reach.
9. Reach transit time will not be a function of ship size or ship direction of travel.
10. Statistics are gathered under steady state conditions.
11. Arrivals are random at the endpoints of the canal in Lake Erie and Lake Ontario.

II. INPUT DATA BASE

A. DATA SOURCES

The data source for the Welland Canal was the St. Lawrence Seaway Authority which supplied "Welland Canal Vessel Transit Analysis Daily Details" for the months of April, June, August, and October, 1971. The data for the months of April and October were influenced by seasonality effects but preliminary examinations indicated that August data would adequately serve the purposes of this study.

The data sources for the Niagara Canal were the Corps of Engineers, Buffalo and North Central districts. The data provided by the Corps consisted of system configuration parameters, transit time distributions for locks and reaches, and finally the fleet data for the Welland-Niagara studies.

B. DATA DESCRIPTION

A complete description of the data used in this study is shown in Appendix D. This section merely provides some of the salient features of the input data.

1. Fleet Data

The fleet data consisted of actual average traffic level in 1971 through the Welland Canal and projected average levels for the years 1980, 1985, 1990, 1995, 2000, 2010, 2020, and 2030. Two estimates for each of the projected levels were given, one representing normal growth and the other representing accelerated growth as shown in Table 1.

Associated with this traffic projection was a fleet composition factor representing the estimated trend towards larger fleet size. Fleet data consisted of three vessel classes, delineated by length of vessel as follows:

TABLE 1. AVERAGE DAILY VESSEL TRANSITS (ships/day)

	Normal Growth	Accelerated Growth
1970	25.50	25.50
1980	26.50	27.40
1985	27.00	28.55
1990	27.50	29.70
1995	28.00	31.15
2000	28.50	32.60
2010	29.50	35.70
2020	30.90	39.80
2030	32.20	44.30

Note: Data for 1970 are actual, for the others are projected.

Class I :   1 - 399 feet

Class II : 400 - 730 feet

Class III: 731 - 1150 feet

A description of the projected fleet composition (percentage distribution by class) for the years 1970 through 2030 is given in Table 2. It may be noted that Class III is comprised of vessels too large to be processed through the Welland Canal.

2. Lock Data

The simulation model, hereon referred to as NETSIM/SHIP (NETwork SIMulator of SHIP movements),[1] represents a lock operation in terms of nine elements as depicted in Figure 1 and delineated in Table 3. Each of these nine elements can be described in the simulation model by either a frequency distribution or an average time of operation. The data for these elements by class size and direction of travel is shown in Table 4. All the locks in the Niagara Canal of four-, five-, and six-lock configurations as well as the four-super-lock Welland configuration were of size 1200' x 110' and used these identical data.

3. Welland Transit Data

The only major treatment of raw data occurred for the "Welland Canal Vessel Transit Analysis Daily Details" for the month of August. This treatment had two objectives.

The first objective was to obtain a transit time distribution for each of the Canal's six entities for calibration purposes. Figure 2 provides a schematic description of the six entities representing the

[1] A complete description of the simulation model is given in Reference (1).

TABLE 2. FLEET COMPOSITION-PERCENTAGE DISTRIBUTION BY CLASS

	Class I (1'-399')	Class II (400'-730')	Class III (731'-1150')
1970	30.00	70.00	0.00
1980	23.30	74.70	2.00
1985	19.85	74.60	5.55
1990	16.40	74.50	9.10
1995	14.00	73.45	12.55
2000	11.60	72.40	16.00
2010	9.60	68.60	21.80
2020	6.60	65.00	28.40
2030	5.30	60.00	34.70

Note: Data for 1970 are actual, for the others are projected.

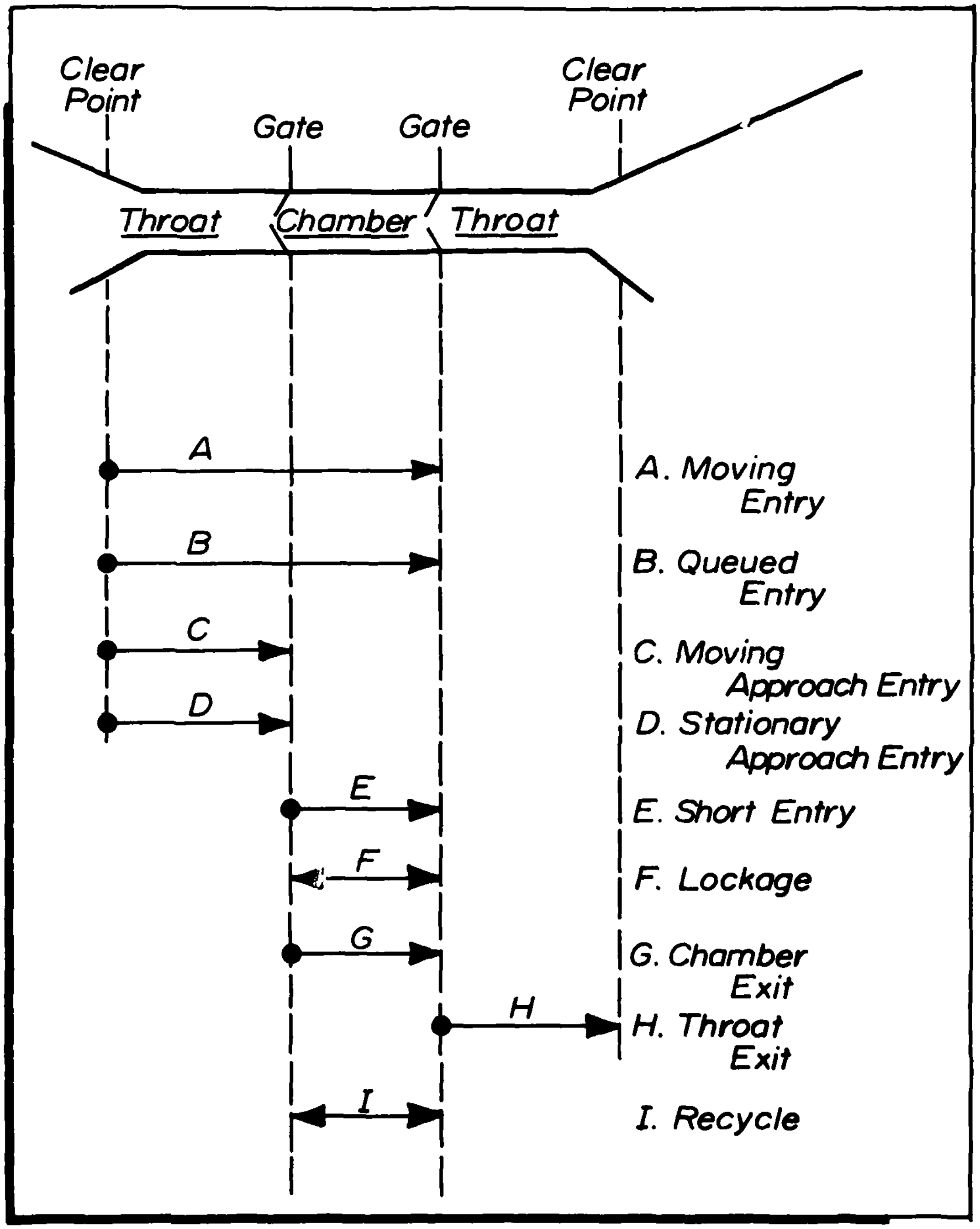

Figure 1. Schematic of Simulated Locking Time Events

TABLE 3. DESCRIPTION OF LOCKING TIME EVENTS

EVENT NAME	DESCRIPTION
A. MOVING ENTRY	into the lock chamber from the Clear Point at the end of the entry throat.
Begins:	when the bow of the ship passes the Clear Point.
Ends:	when the gates begin to close astern of the ship.
B. QUEUED ENTRY	into the lock chamber from the head of the queue adjacent to the Clear Point.
Begins:	when the gates are fully open and the chamber is free.
Ends.	when the gates begin to close astern of the ship.
C. MOVING APPROACH ENTRY	from the Clear Point to a position in the entry throat just clear of the entry gate.
Begins:	when the bow of the ship passes the Clear Point.
Ends:	when the ship comes to rest in the entry throat.
D. STATIONARY APPROACH ENTRY	from the head of the queue adjacent to the Clear Point to a position in the entry throat just clear of the entry gate.
Begins:	when the bow of the ship passes the Clear Point.
Ends:	when the ship comes to rest in the entry throat.
E. SHORT ENTRY	into the lock chamber from a stationary position just clear of the entry gate in the entry throat.
Begins:	when the gates are fully open and the chamber is free.
Ends:	when the gates begin to close astern of the ship.
F. LOCKAGE	of a ship at rest in the chamber.
Begins:	when the entry gates begin to close astern of the ship.
Ends:	when the exit gates are fully opened after the change in water level.
G. CHAMBER EXIT	from chamber to position where the ship's stern clears the exit gate.
Begins:	when the exit gates are fully opened after the change in water level.
Ends:	when the ship's stern is clear of the exit gate.

TABLE 3. CONTINUED

EVENT NAME	DESCRIPTION
H. THROAT EXIT	from position where the ship's stern clears the exit gate to the Clear Point at the end of the exit throat.
Begins:	when the ship's stern is clear of the exit gate.
Ends:	when the stern of the ship passes the Clear Point.
I. RECYCLE	of the water level with no ship in the chamber.
Begins:	when the gates begin to close.
Ends:	when the opposite gates are fully open to receive an incoming ship.

TABLE 4. LOCK DATA FOR WELLAND-NIAGARA STUDIES

(Average Times of Operation in Minutes)

Lock Elements	Direction	Class I	Class II	Class III
A. MOVING ENTRY	Up	21	28	37
	Down	20	26	34
B. QUEUED ENTRY	Up	24	31	40
	Down	21	29	38
C. MOVING APPROACH ENTRY	Up	14	16	20
	Down	12	14	19
D. STATIONARY APPROACH ENTRY	Up	17	19	23
	Down	15	17	22
E. SHORT ENTRY	Up	12	16	23
	Down	11	15	23
F. LOCKAGE (PROCESS)	Up	14	16	18
	Down	14	16	18
G. CHAMBER EXIT	Up	8	9	10
	Down	7	8	10
H. THROAT EXIT	Up	6	7	8
	Down	5	7	8
I. RECYCLE	Up	11	11	11
	Down	11	11	11

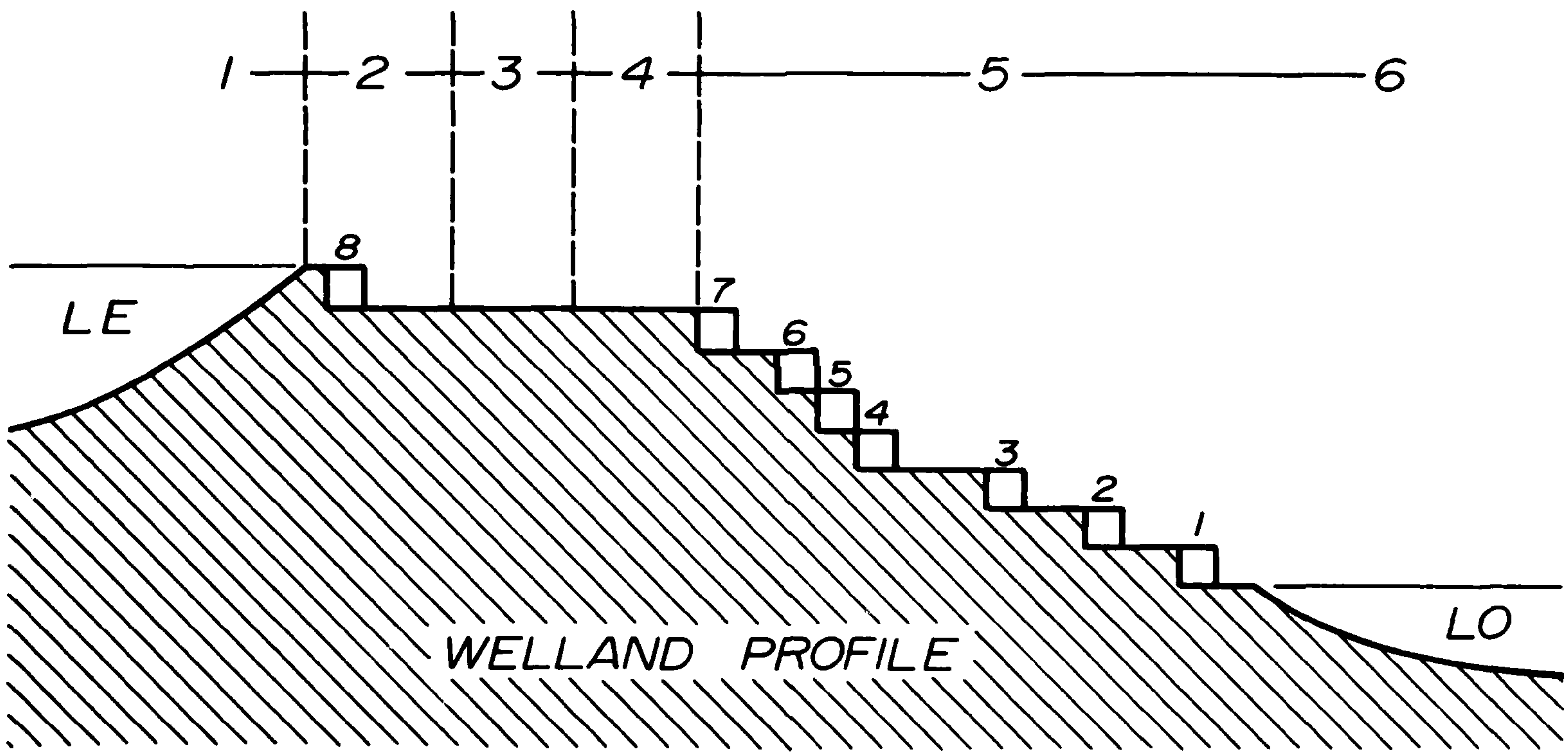

Figure 2. Simulated Representation of the Welland Canal

Welland Canal, and Table 5 summarizes the corresponding transit data.

The second objective was the derivation of a transit time equation as a function of system conditions which would be used to predict the expected transit time through the canal during simulation. The results of this treatment are given in Appendix B. Note that the corresponding transit time equation for the proposed Niagara Canal had to be derived through an EDB simulation run; the results of which are also given in Appendix B. An EDB run was not necessary for the Welland Canal, however, since empirical data were available.

TABLE 5. TRANSIT DATA FOR WELLAND - AUGUST 1971

Explanation	Simulation Reach Identification Numbers	UPSTREAM Mean (hours)	UPSTREAM % of Total Transit Time	DOWNSTREAM Mean (hours)	DOWNSTREAM % of Total Transit Time
Downstream Waiting Area	2150	0	0	2.483677	19.66
Reach 4*	2200	1.643601	12.35	1.156160	9.15
Reach 3	2250	1.976400	14.85	1.948431	15.42
Reach 2	2300	1.012270	7.61	1.269250	10.05
Reach 1**	2350	6.158961	46.29	5.775386	45.72
Upstream Waiting Area	2400	2.513889	18.89	0	0
	Total	13.305121	99.99	12.632904	100.00

*Reach 4 extends from Bridge 18 to Lock 8 (Guard Lock).

**Reach 1 extends from Lock 1 to Lock 7.

III. CALIBRATION

A. THE WELLAND CANAL

The simulation run for the existing Welland Canal network, modeled as a set of six reaches under a 1971 traffic load, served as the base run for subsequent analysis of various other configurations. This simulation methodology did not use Monte Carlo sampling from random probability distributions for a vessel's transit time, but rather utilized the empirical transit time-system condition relationship obtained through regression as explained in Appendix B.

Thus, at the moment of a vessel's entrance into the Welland Canal, its expected canal transit time was computed as a function of the existing system conditions. Transit through individual reaches was subsequently accomplished through random sampling from prior distributions whose means were empirically determined fractions of the expected canal transit time.

Since the technique described above constitutes, in principle, a projection of the empirical relationship rather than true Monte Carlo simulation, it will be hereon referred to as "ETT simulation." The projection of this relationship is valid for only finite deviations from the 1971 traffic load, in fact only for the range of the empirical data from which the relationship had been obtained. Since the traffic load for some of the future periods in the analysis falls outside this range, queuing theory as explained in Appendix C was used to supplement ETT simulation.

The calibration run, then, consists of an ETT simulation of the existing Welland Canal under a 1971 traffic load. A fleet mix of 30 percent Class I and 70 percent Class II was used. Results of the simulation run, shown in Table 6, are differentiated by direction and are given in both

TABLE 6. SIMULATION TRANSIT DATA FOR THE EXISTING WELLAND

USING 1970 TRAFFIC DENSITY

Simulation Identification Number		2150	2200	2250	2300	2350	2400		
		Upstream Waiting Area	Bridge 18 to Lock 8	Bridge 10 to Bridge 18	Lock 7 to Bridge 10	Lock 1 to Lock 7	Downstream Waiting Area	Total	Average
Average Transit Time (minutes)	UP	-	97	116.7	59.8	363.8	148.5	786	
		(0)	(1.616)	(1.945)	(.997)	(6.06)	(2.475)	(13.1)	
									757
									(12.617)
	DOWN	143	66.5	112	73	332.4	-	727	
		(2.38)	(1.11)	(1.867)	(1.217)	(5.54)	(0)	(12.116)	

NOTE: Conversion to hours appear in parentheses.

minutes and hours. Transit times through individual sections of the canal compare favorably with the empirical data (see Table 5). The latter are understated by about 4 percent for downstream transit and by about 1.5 percent for upstream travel with an overall underestimation of about 2 percent.

B. THE PROPOSED NIAGARA CANAL

In order to determine the relationship between the Welland Canal and the proposed Niagara Canal, the minimum time to transit the latter for its various configurations was calculated from the input data as follows:

	Transit through Locks (minutes)		Transit through Reaches (minutes)	Total (minutes)	
	UP	DOWN		UP	DOWN
4-Lock Niagara	240	228	527	767	755
5-Lock Niagara	300	285	506	806	791
6-Lock Niagara	360	342	481	841	823

These figures assume an average locking time of 60 minutes including entry and exit and, in fact, represent the input data for Class II vessels. The minimum times shown in this table assume that all locks would be properly set to receive a vessel without any delay. Under such circumstances, the minimum transit time through the Niagara Canal for all configurations (except upstream transit for the four lock Niagara) is still greater than the mean transit time through the Welland Canal under normal traffic. This suggests that in the subsequent simulations, the proposed Niagara Canal might serve as the backup alternative for a Welland under congestion, except for Class III vessels which would be too large to have a channel choice. This is precisely borne out in the later studies although traffic tends to equalize in the long run due to the changes in fleet composition.

IV. THE SINGLE WELLAND STUDIES

Under this classification, there are again three configurations:

1. the existing Welland with no further major improvements,
2. the improved Welland with nonstructural improvements,
3. the improved Welland with structural improvements consisting of four new super locks of 1200' x 110' dimensions and, in addition, a guard lock to compensate for fluctuations with Lake Erie.[1]

Since the study of each network was unique in itself, no general introduction is supplied except to state the primary need of these studies was to establish the expected limits of service of each network.

A. ESTABLISHING THE CAPACITY OF THE EXISTING WELLAND

A reasonable estimate of the capacity of the Welland Canal may be derived from a number of ways. Three techniques that prominently come to mind are Monte Carlo simulation, analytical methods such as queuing theory and regression analysis, and a qualitative appraisal based on the nominal capacities of individual locks in the Welland.

The utility of Monte Carlo simulation models for waterway systems analysis has been previously demonstrated (7). The special case of a sophisticated control system at Welland poses problems for such simulation, however. In particular, rules and procedures such as the priority rating for ships proceeding toward lock 7 over those which have passed it, the preferential treatment to faster ships if a gap develops in the traffic toward lock 7, special rules for heavy one-way traffic and for ships most susceptible to wind and fog are difficult to model.

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[1]Existing locks would be leveled (Source: St. Lawrence Seaway Authority).

For these and other reasons, Monte Carlo simulation has not been employed in the Welland studies.

Discussions with the St. Lawrence River Authority have indicated that a maximum of 40 lockages per day can be accomplished at the Welland locks. This accomplishment can only occur under conditions of favorable weather, of large queues (in the order of 10) on both sides, and of normal operation. Any deviations from these conditions such as a fog or an accident leads to a rapid increase in the queue. A more reasonable level of capacity quoted is around 36 lockages per day or about 90 percent of nominal capacity. Increasing the capacity in terms of vessels per day or lockages per day is, however, only one measure of performance. What matters most to shipping companies is the total canal travel time, including both the time they wait to enter the canal and the actual canal transit time itself. This total travel time could be worsened even though capacity in terms of lockages per day is increased. For example, lock utilizations of the order given above require large queues on either side of the lock, and hence it is necessary to have many vessels inside the canal at any one time. Then, even though the input rate and output rate from the canal were increased, the canal transit times associated with this level of operation could also be extremely large.

The capacity of the Welland Canal may also be estimated by way of analytical methods. Two such methods mentioned above and employed in this study are the queuing and regression (ETT simulation) models.

Results

Given the arrival rate in terms of expected lockages per day[2]

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[2]This characterizes one of the assumptions of this study, viz., there will be no tandem or multiple lockages. In reality, these constituted about 11 percent of the arrival rate in 1971, a decline from 20 percent in 1965.

and the largest lock service time, the ratio of these two parameters provides a measure of system capacity. When this ratio reaches one or 100 percent, the system is said to have found its nominal capacity.

Discussions with the St. Lawrence River Authority revealed that lock 7, which is the bottleneck on the Welland Canal, had a lock cycle of 72 minutes or a single lockage time (including ship entry and exit) of 36 minutes. Solving for the arrival rate in terms of lockages per day needed to reach the nominal system capacity, this figure turns out to be exactly 40 (lockages per day), no doubt the source of the earlier information.

In a similar manner the expected system capacity in percentage for each year of projected growth can be calculated, and these results are shown in Table 7 for both normal and accelerated rates. These figures are lower than the lock utilizations that are actually realized because the effects of coordinating tandem and multiple lockages are not included. If the latter continue to develop in future traffic, the canal could saturate earlier than Table 7 would indicate.

The results of the ETT simulation runs are shown in Table A1[3] and additionally are plotted along with the results of the queuing model in Figure 3. In observing the ETT curve, the statement concerning the range of the empirical data over which the regression equation was fitted is once more brought to light.

To draw inferences regarding Welland capacity, it is necessary to set forth a definition of capacity. (It is assumed here that the definition that is of interest would consider the transit time associated with some particular level of input traffic or lock utilization rather than the nominal capacity that has been referred to previously.) One can obtain

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[3]Collected in Appendix A.

TABLE 7. THE EXISTING WELLAND CANAL - CAPACITY SUMMARY

	Normal Growth Projections		Accelerated Growth Projections	
Year	Arrival Rate (Number of Lockages per Day)	% of Nominal Capacity	Arrival Rate (Number of Lockages per Day)	% of Nominal Capacity
1971	25.5	63.7		
1980	26.5	66.2	27.4	68.5
1985	27.0	67.5	28.55	71.4
1990	27.5	68.7	29.7	74.2
1995	28.0	70.0	31.15	77.9
2000	28.5	71.2	32.6	81.5
2010	29.5	73.7	35.7	89.2
2020	30.9	77.2	39.8	99.5
2030	32.2	80.5	44.3	arrival rate greater than lock service rate

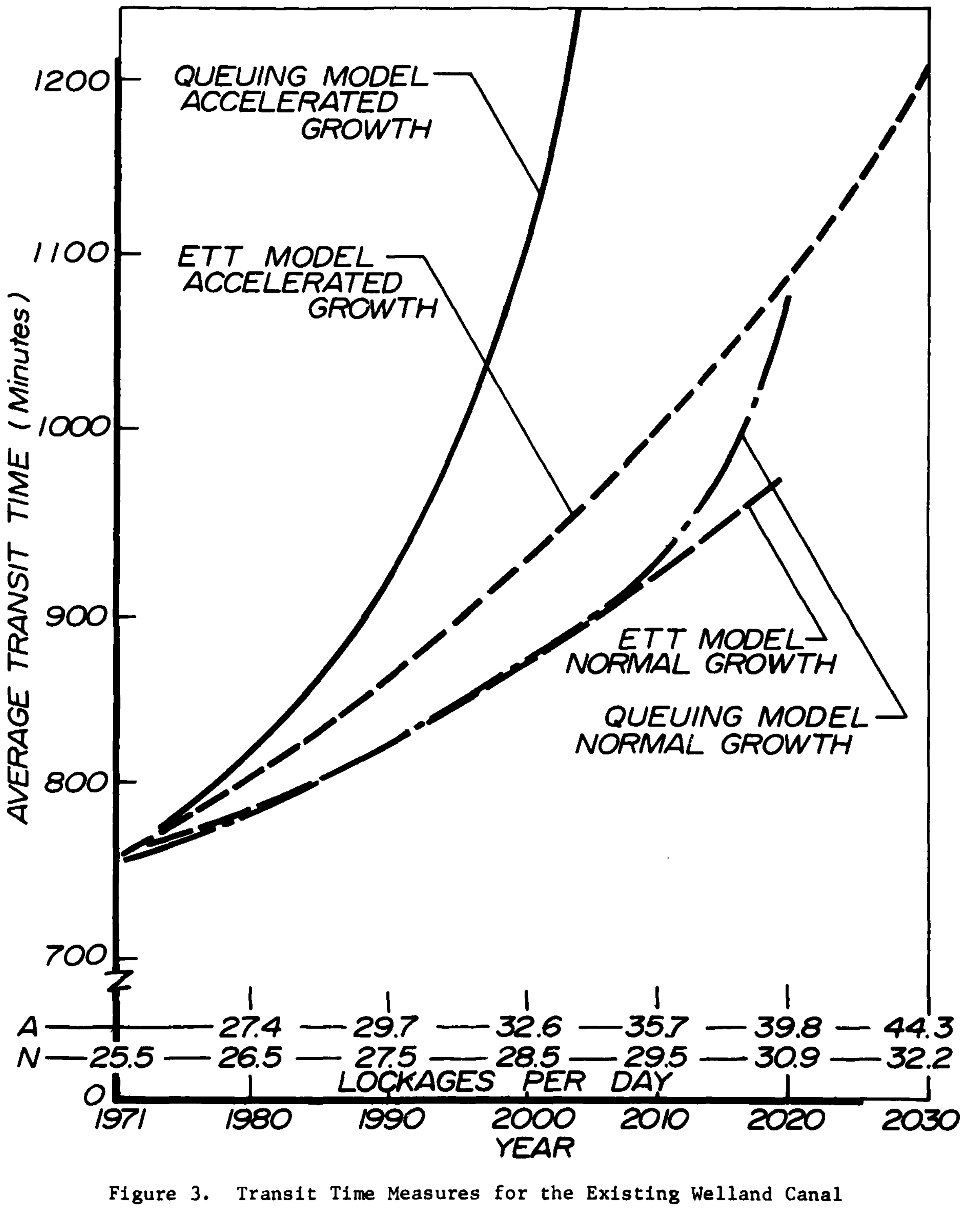

Figure 3. Transit Time Measures for the Existing Welland Canal

some assistance on this point from the use of 75 percent of nominal capacity in literature as an indication of an economical or practical level oi capacity (for example, see (8), (9), (10)). If this criterion is used to indicate capacity, it is met under accelerated growth projections as early as 1990 and under normal growth projections at 2010.

In Figure 3, these two measures fall in those portions of the curves where the slopes are changing rapidly. This indicates that further traffic can be introduced into the canal; however, the delays associated with such additional increases would rapidly accelerate. Further, the traffic figures used for 1990 accelerated and 2010 normal projections are 29.7 and 29.5 lockages per day, respectively, and represent the seasonal daily average for the Welland Canal. Traffic during certain periods of the season may be greater than these seasonal averages, however.

The statement "Welland capacity is reached in 1990 under accelerated projections and in 2010 under normal growth projections," therefore, involves the following assumptions:

1. Capacity used in the above statement is 75 percent of the maximum theoretical capacity.
2. The traffic projections used are seasonal averages.
3. The traffic projections used are the number of lockages per day and not vessels per day.
4. The effects of coordinating tandem and multiple lockages are not included.
5. Structural as well as nonstructural operations as in existence in 1971 are assumed to remain unchanged.

The assumptions given above also apply to the next two studies.

B. ESTABLISHING THE CAPACITY OF THE IMPROVED WELLAND (NONSTRUCTURAL)

In the ETT simulation of this task, the effects of various nonstructural improvements were assumed to have resulted in first, a reduction of the lock cycle from 72 minutes to 70 minutes; and second, the translation of this efficiency into a net transportation savings of 2 hours in round-trip transit time.

Thus, the simulation itself consisted of incorporating these efficiencies in the ETT model's transit time distributions derived for each vessel when it arrives at the call-in-point and therefore, is again an extrapolation of a current empirical relationship to future demand. Hence, this technique suffers from the same shortcoming as the previous one and is valid only for finite deviations from current capacity.

Capacity is related to the input stream as shown in Table 8. The capacity figures represent a ratio of the input rate to the lock service rate where the latter assumes a lock service time of 35 minutes per lockages. Nominal capacity for this system is 41 lockages per day, but using the criterion from the previous section, 75 percent of system capacity is reached at a vessel arrival rate of about 31 lockages per day. An estimate of the transit time associated with these levels of system utilization can be obtained from Figure 4. This figure compares the simulation and queuing model results; the similarity of behavior between this and the preceding network is as expected.

C. ESTABLISHING THE CAPACITY OF THE IMPROVED WELLAND (STRUCTURAL)

A preliminary study of this network (for a diagram, see Appendix D) consisted of a Monte Carlo simulation using the locking data provided by the Corps. The network was subjected to traffic demands for years 1980, 1985, and 1990. Further experimentation was deemed unnecessary as the

TABLE 8. THE WELLAND CANAL WITH NONSTRUCTURAL IMPROVEMENTS - CAPACITY SUMMARY

Year	Normal Growth: Arrival Rate Lockages/day	Normal Growth: % of Nominal Capacity %	Accelerated Growth: Arrival Rate Lockages/day	Accelerated Growth: % of Nominal Capacity %
1980	26.5	64.4	27.4	66.6
1985	27.0	65.6	28.55	69.4
1990	27.5	66.9	29.7	72.2
1995	28.0	67.9	31.15	75.7
2000	28.5	69.3	32.6	79.2
2010	29.5	71.8	35.7	86.8
2020	30.9	75.1	39.8	96.7
2030	32.2	78.3	44.3	arrival rate exceeds service rate

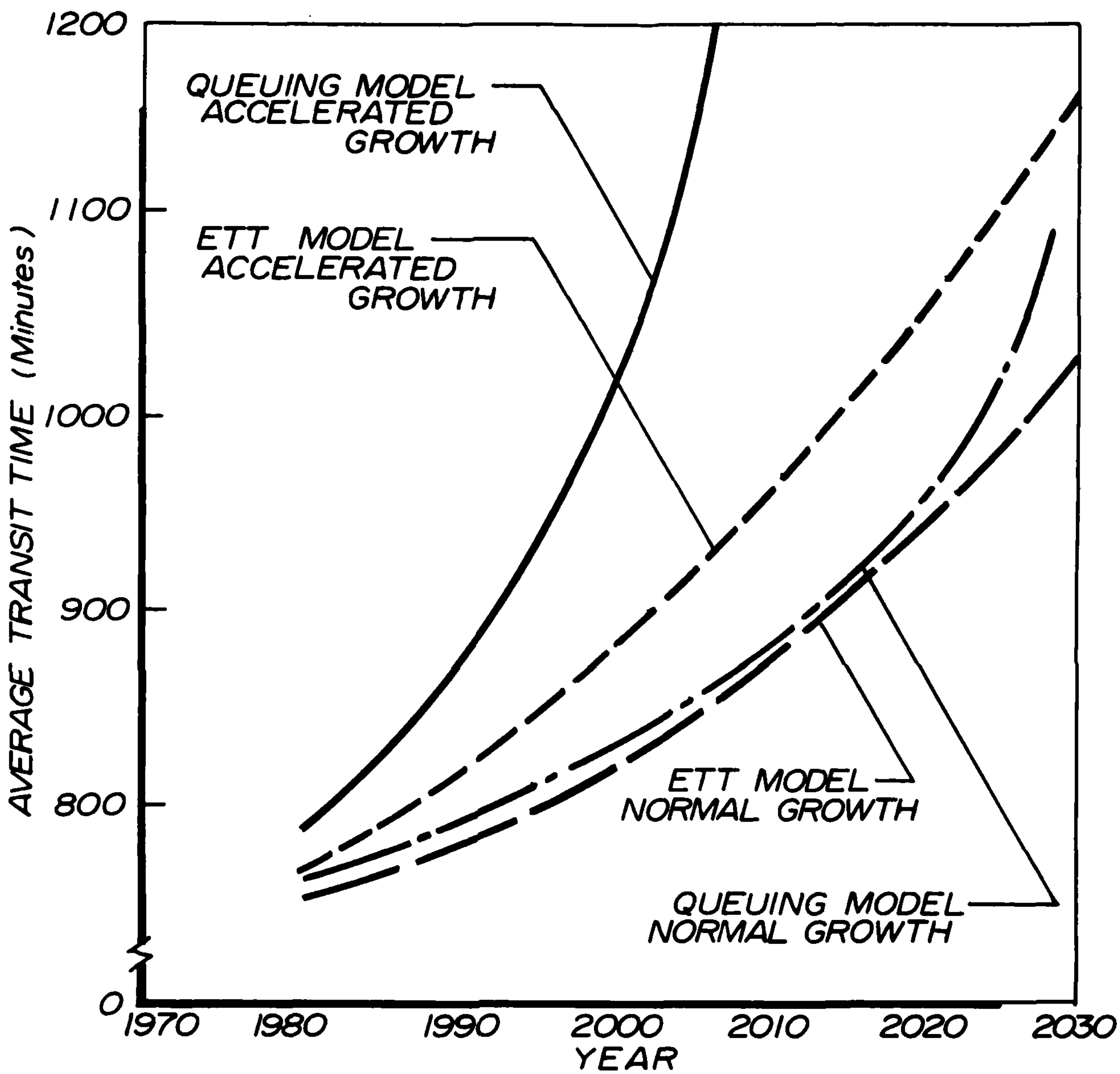

Figure 4. Transit Time Measures for the Nonstructurally Improved Welland Canal

system was judged to have reached its capacity. The primary reason for this was the data providing for an average lock cycle of 120 minutes (or a single lockage time of 60 minutes including vessel entry and exit). At this service rate, nominal system capacity is only about 24 lockages per day.

Subsequent discussions with the St. Lawrence Seaway Authority indicated that a lock cycle time of 80 minutes might well be attainable. The queuing model was therefore employed to develop a series of response curves where different lock cycle times were employed. The results of this analysis are shown in Figure 5, where the different curves represent lock cycle times ranging from 72 minutes to 96 minutes.

These results stress the ramarkable sensitivity of system capacity to lock cycle times and suggests that significant economics exist in reductions in say lock approach and entry time. Large vessel sizes permit an increase in tonnage capacity; however, the resultant loss of maneuverability affecting a more cautious and slower lock approach leads to a decrease in system capacity. This tradeoff indicates that significant implications for fleet and facility design may be obtained from the type of analysis made above. The simulation model is particularly useful in this context since it contains a detailed representation of the lock and can, therefore, provide fast computations of the various tradeoffs as mentioned above--assuming of course that the relationship between vessel size and locking time can be quantified properly as input data.

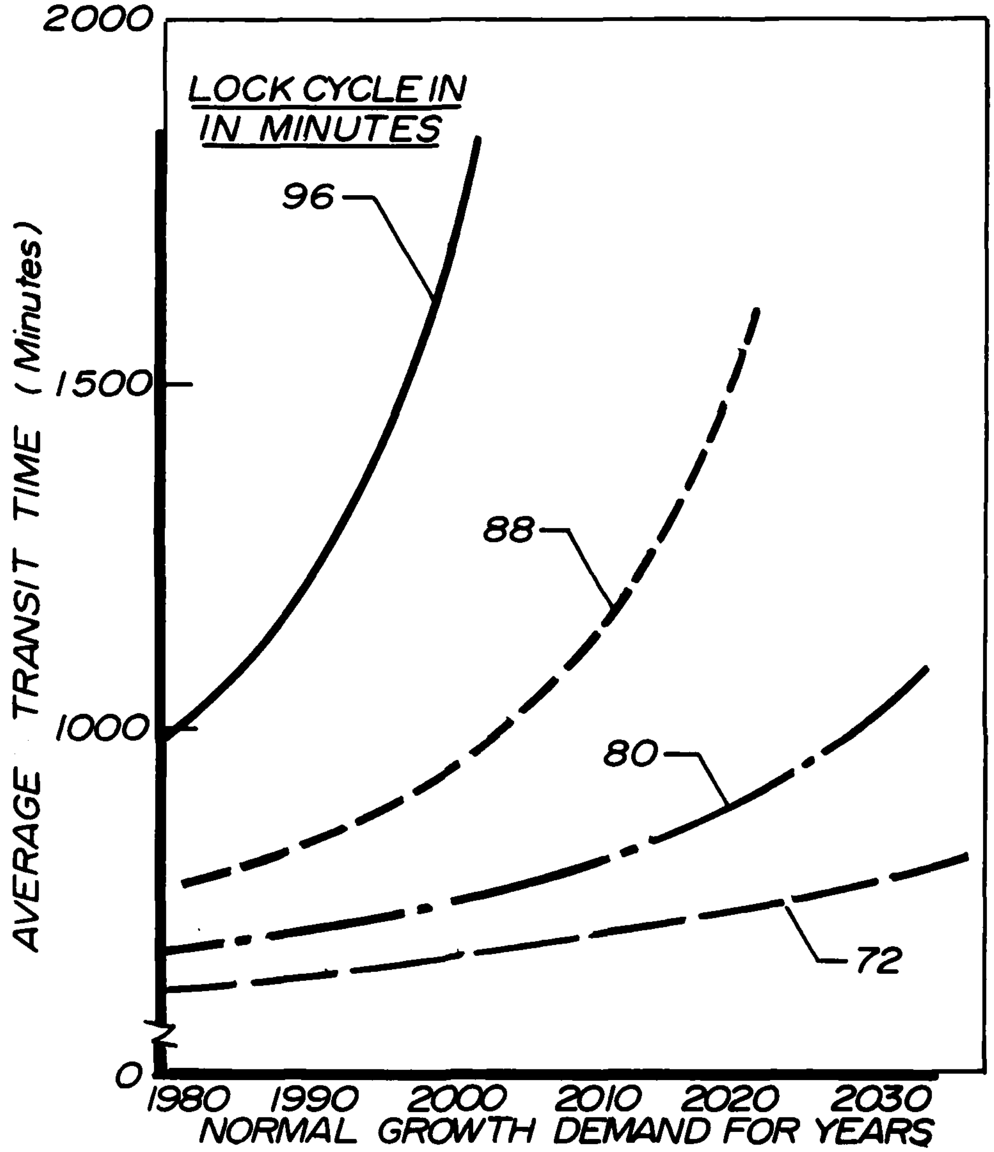

Figure 5. Transit Performance for the Structurally Improved Welland Canal

V. TWIN CANAL STUDIES

A. SIMULATION RESULTS

Three configurations were simulated in these studies. All configurations had the Welland Canal in common, but the Niagara Canal consisted of either four, five,or six locks in series. The latter, therefore, also contained either seven, eight, or nine reaches as shown in the network diagrams in Appendix D.

Passing was not permitted in any of the reaches except the end reaches of the Niagara Canal which form the outliers of the lakes. Vessels originate at ports and arrive at channel assignment decision nodes where NETSIM/SHIP's channel assignment mechanism is set in motion to determine the channel offering the least expected transit time.

The simulation experiments subjected each network to increasing transport demand from 1980 through to 2030, if necessary, in five year increments up to year 2000 and in ten year increments thereafter. Each simulation was examined for signs of saturation to determine if the next higher level of demand experiment was necessary.

The principal parameters of interest in these simulations were transit time, delays, and lock utilizations. The latter two measures could only be observed at the locks in the Niagara Canal, and performance through the Welland Canal was assessed in terms of transit time.

1. Welland-Four Lock Niagara Subsystem

The overall behavior of this system can be captured in a graphical display of average transit time as shown in Figure 6. Certain other selected system parameters are exhibited in Table A.2.

The tendency toward curvature in Figure 6 may be inferred from a closer examination of system parameters for each canal. The number of

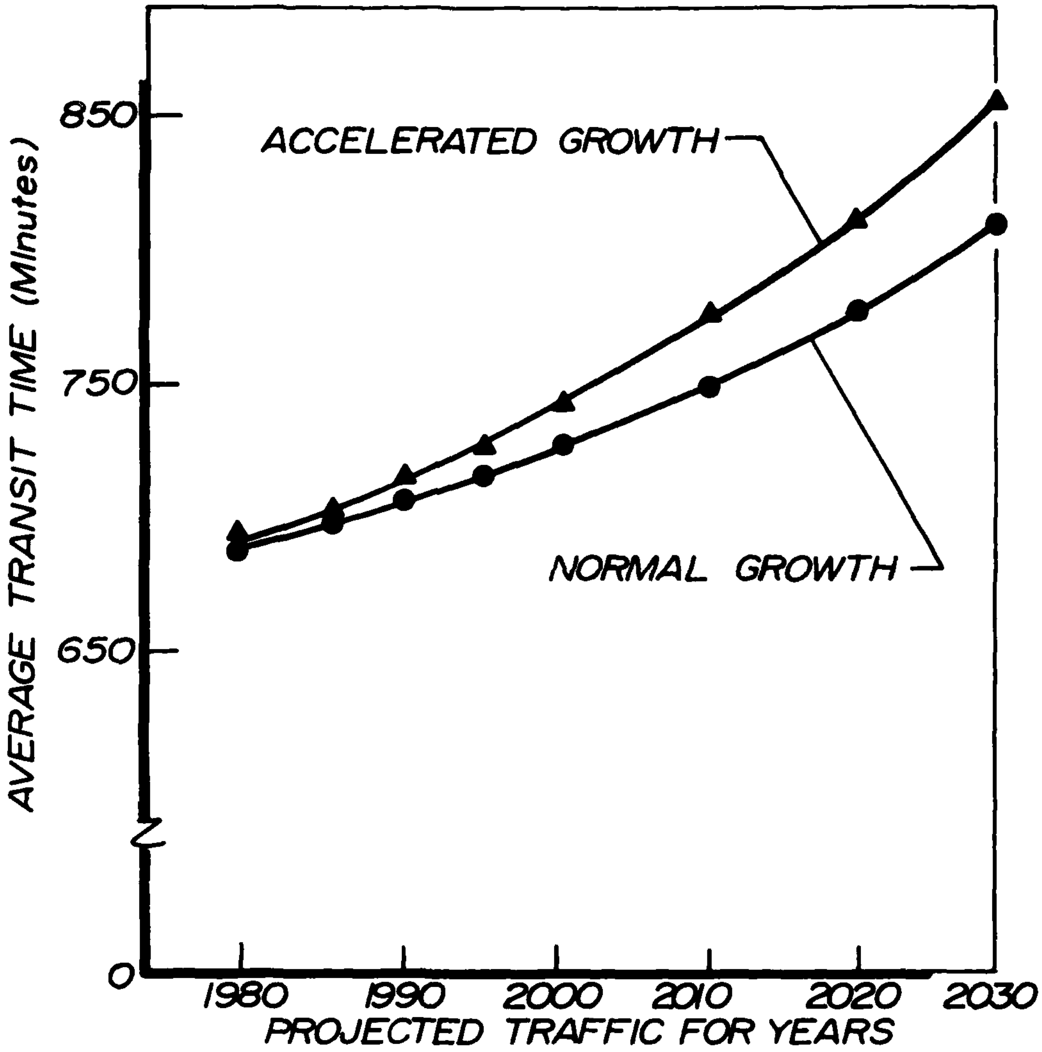

Figure 6. Average Transit Time for the Welland-
Four Lock Niagara Subsystem

journeys and the average transit time through each canal are given in Table A.3. The average transit time through the Welland drops from the calibration run value of 757 minutes (12 hours and 36 minutes) in 1971 to 673 minutes (11 hours and 13 minutes) in 1980. Throughout the rest of the period of experimentation, the average transit time levels off because the decreasing traffic through Welland falls outside the range of the empirical data from which the ETT relationship had been obtained. One can note however, that in conjunction with the decrease in the Welland traffic, the composition of the fleet becomes dominated in time by Class II vessels. The load factor through the Niagara Canal, on the other hand, increases significantly from period to period, this being in large part due to the projected increase in vessels of Class III.

The system performance measures for the Niagara Canal in terms of delays and lock utilization are given in Table 9. The canal is extremely underutilized and is probably not in steady state until about 1990. In year 2030 with about 12 ships per day, average canal delay is about 2-1/2 hours with lock utilizations approximately 60 percent.

2. Welland-Five and Six Lock Niagara Subsystems

The simulation results for these configurations were very similar to those for the Welland-Four Lock Niagara network. The main items of departure from the latter were the degree of traffic diversion from the Welland to the Niagara in Classes I and II and the average transit time through the Niagara Canal.

The average system transit times for these configurations are plotted in Figure 7. The occurrence of high delays at high utilization rates, contributing to the curvature, is again established in Tables 10 and 11 and in Tables A.4, A.5, A.6, and A.7.

TABLE 9. THE NIAGARA CANAL PERFORMANCE MEASURES FOR THE WELLAND-FOUR LOCK NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

Year	Average Canal Delay (min)	Total Canal Delay (min)	Average Lock Utilization (%)	Maximum Delay at any Single Lock (min)
1980	2.8	76	6.4	47
1985	9.7	397	10.5	65
1990	9.2	452	12.8	95
1995	18.1	1,226	18.1	101
2000	36.9	3,539	24.4	134
2010	47.2	5,941	29.2	251
2020	84.6	13,802	45.6	305
2030	141.7	29,598	55.4	427

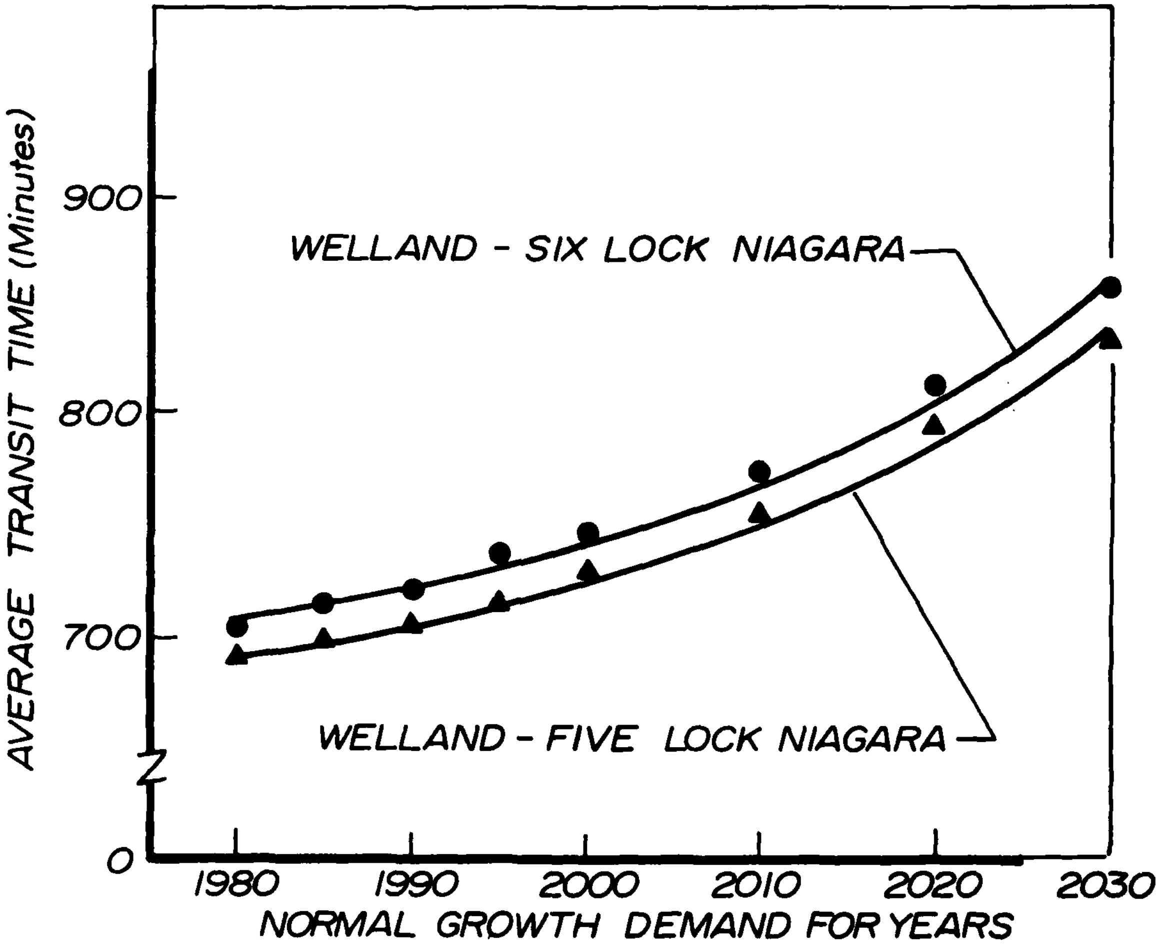

Figure 7. Average Transit Time for the Welland-Five and Six Lock Niagara Subsystems

TABLE 10. THE NIAGARA CANAL PERFORMANCE MEASURES FOR THE WELLAND-SIX LOCK NIAGARA SUBSYSTEM

	Normal Growth Demand for Years							
	1980	1985	1990	1995	2000	2010	2020	2030
Average Canal Delay (minutes)	-	4.5	7.3	18.1	37.2	49.8	90.1	158.9
Total Canal Delay (minutes)	-	95.0	279.0	1095.0	2930.0	5435.0	13,751.0	28,743.0
Average Lock Utilization (%)	2.9	6.7	10.8	25.2	25.2	32.7	46.3	57.5
Maximum Delay at Any Single Lock(minutes)	-	53.0	62.0	103.0	124.0	191.0	207.0	335.0

TABLE 11. THE NIAGARA CANAL PERFORMANCE MEASURES FOR THE WELLAND-FIVE LOCK NIAGARA SUBSYSTEM

	Normal Growth Demand for Years							
	1980	1985	1990	1995	2000	2010	2020	2030
Average Canal Delay (minutes)	-	3.3	6.5	21.3	29.1	43.1	72.7	134.8
Total Canal Delay (minutes)	-	10.0	242.0	1258.0	2299.0	4863.0	11,061.0	26,091.0
Average Lock Utilization (%)	2.6	6.8	10.8	17.0	23.2	27.9	44.2	53.9
Maximum Delay at Any Single Lock(minutes)	-	-	53.0	98.0	126.0	178.0	189.0	301.0

The behavior of the five-lock Niagara usually lay in between those of the four- and six-lock configurations although no statistical difference could be established in many cases.

B. DISCUSSION OF RESULTS

The results of the Monte Carlo simulations suggest that any one of the twin-canal configurations would function adequately in meeting transport demand up to and including that for 2030. Although the Welland-Four Lock Niagara network seems to offer lower transit time than the others, no absolute statistical difference between the performances could be established. Therefore, the desirability of a particular configuration must rest on other economic criteria such as initial capital outlay and operating and maintenance expenditures.

If the system interactions remain the same, and if the locking time remains constant, one can speculate on the saturation arrival rates, i.e., that level of traffic which would give rise to high lock utilizations. Given the assumptions above, the lock utilizations can be calculated as the ratio of the arrival rate to the lock service rate and as such are given below.

Lock Utilization	Mean Service Time $1/\mu$	Arrival Rate λ
75%	72 minutes	15.0 ships/day
80%	72	15.99
90%	72	18.0
99%	72	19.8

The above relationships are exact and indicate that if 19.8 ships per day arrive into the Niagara Canal (not the Welland-Niagara subsystem) where the projected average lock service time is 72 minutes, then the

locks will experience a 99 percent utilization rate. To obtain the life of a Welland-Niagara twin-canal subsystem, it is further necessary to consider: 1) the capacity of the Welland, 2) potential increases in capacity through further nonstructural improvements, and 3) trends in fleet composition.

In summary, the simulations suggest that the primary benefits from the construction of a twin canal are transportation savings not due to large reductions in total canal transit time, but rather due to reduced ship idle time in combination with the increased capacity permitted by larger lock dimensions.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The following points summarize the conclusions from the individual network simulations. A pictorial summary is given in Figures 8 and 9.

1. Performance statistics from simulations of the twin-canal networks suggested that any of the four-, five-, or six-lock Niagara Canal in combination with Welland would perform equally well under projected traffic up to year 2030. This conclusion must be tempered by the following observations:

   i. All twin-canal simulations used a single set of locking data. Under these conditions, no statistical differences could be established between any of the three configurations. Changes in locking data among the various networks could revise this result.

   ii. In connection with the above and specifically with regard to the alternative Niagara Canal configurations, the traffic was completely dominated by Class III vessels and as such an average lock processing time of 70 minutes was obtained. Bearing in mind that this figure refers to a 1200' x 110' lock and that the lock data were based on original observations at Poe Lock, comparison may be made with the following lock operations:

	Identification	Dimension	Average Lift	Average Time Per Lockage
Welland Canal	existing locks	860' x 80'	43'-48'	36 minutes
	with nonstructural improvements	860' x 80'	43'-48'	35 min. (expected)
	super locks	1200' x 110'	80'	40 min. (expected)
	Eisenhower-Snell	860' x 80'	38'-49'	37 min. (for large vessels)

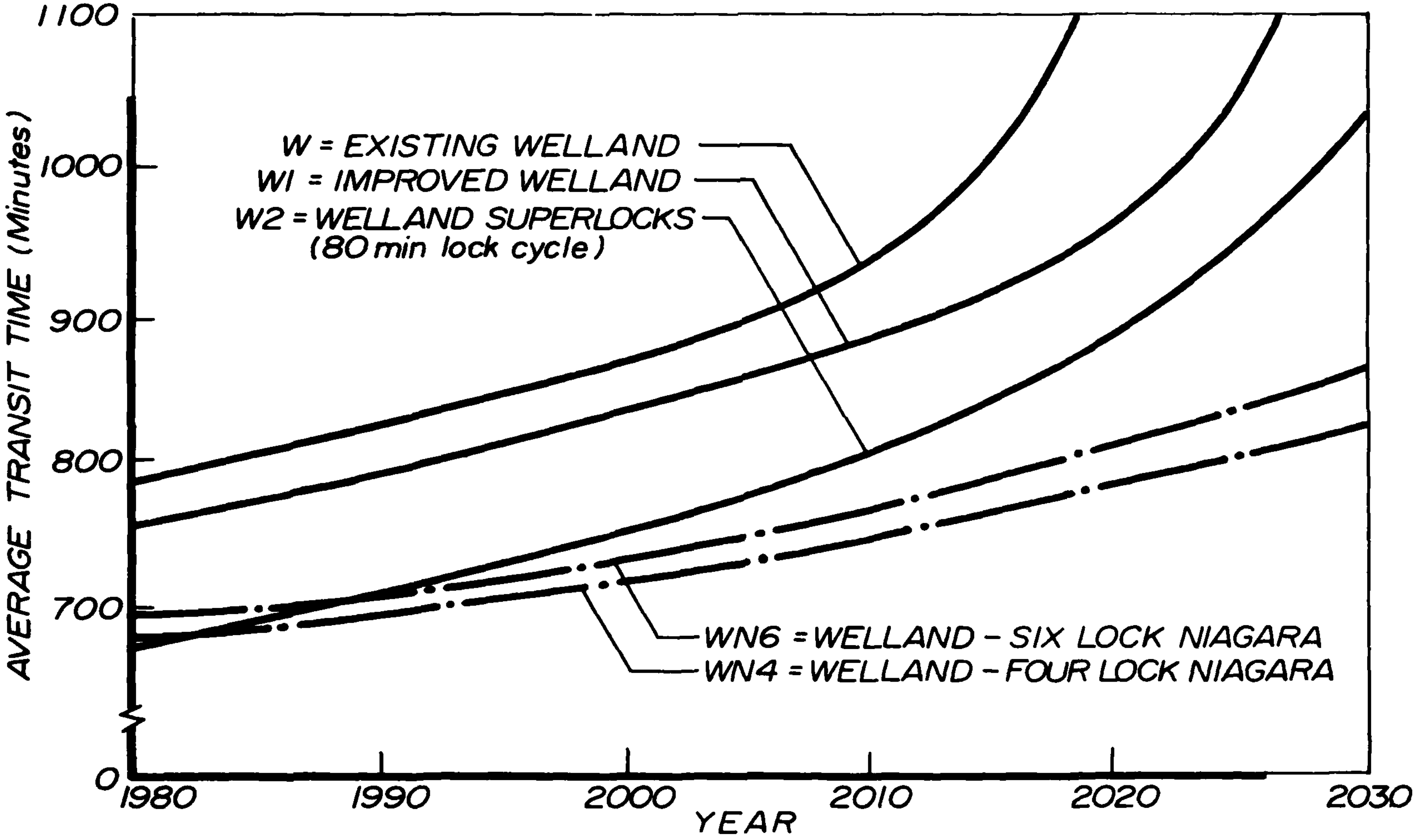

Figure 8. Transit Summary under Normal Growth

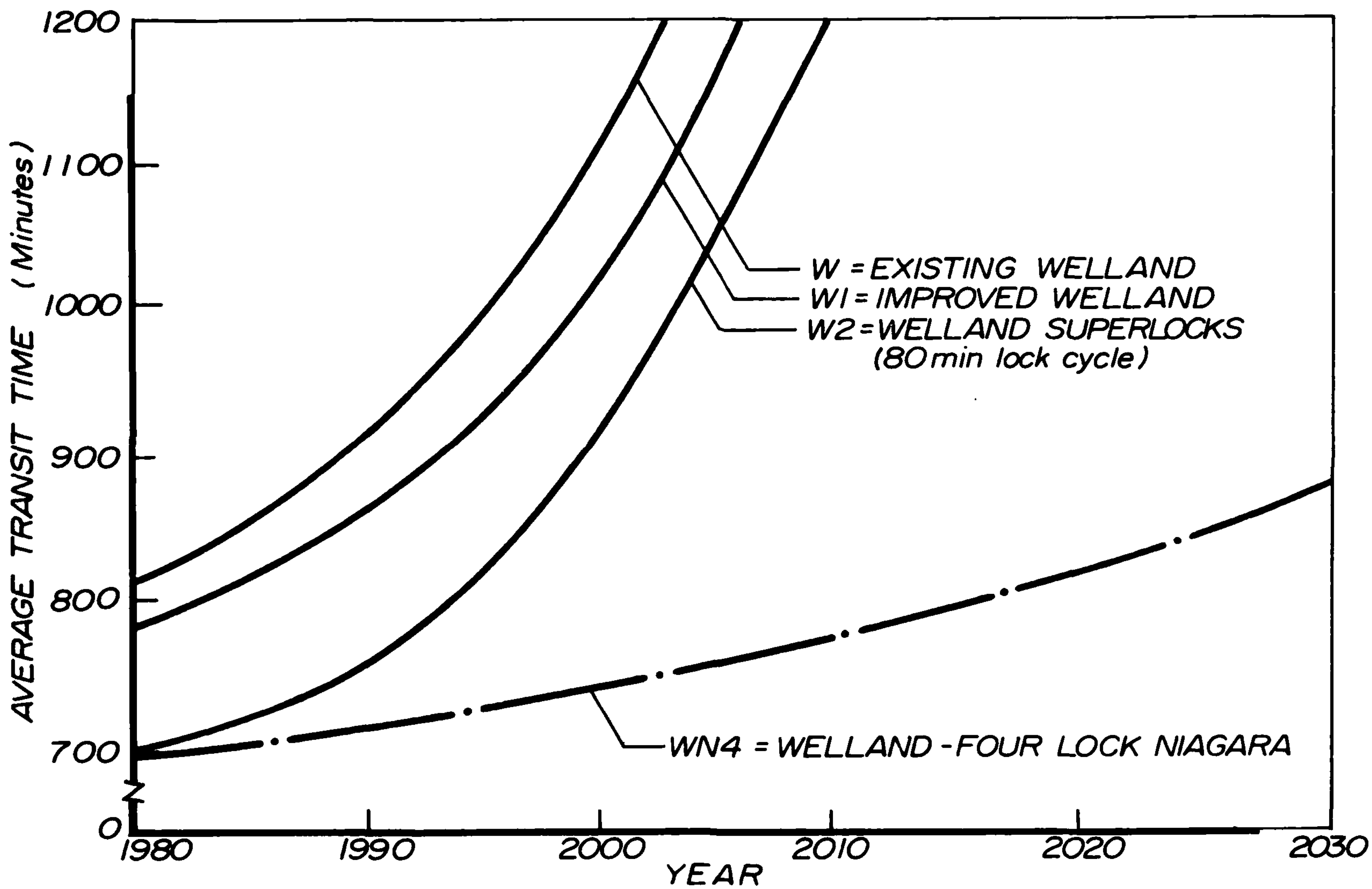

Figure 9. Transit Summary under Accelerated Growth

Thus, any major improvement in lock design (or operations) invalidating the use of the 70-minute locking time could give rise to significant increases in benefits in the form of reduced delay and higher capacity.

iii. The simulation runs assumed a uniform and smooth operation in the channels (reaches) connecting the locks. No channel delays were incorporated into the model. This is not a grave problem for the twin-canal studies since the systems were never in serious congestion. At higher utilization rates, however, major channel delays could "deregulate" vessel interarrival patterns leading to larger delays.

iv. The study assumed a SOQA[1] (Serve Opposing Queues Alternately) rule and further included a service lookahead feature so that no "unnecessary" ship delays occurred.

2. Given the locking data for the Niagara Canal, immediate benefits of a twin-channel relative to the calibration run (viz., the existing Welland) were manifested in the form of reduced delays and increased capacity but not in reduced canal transit time. This is readily evident when one considers the minimum time required to transit the Niagara under the null condition as earlier shown on page 23.

3. Given the input data for the Niagara Canal, the ETT mechanism channeled the bulk of the traffic in the early years of traffic projection into the Welland Canal with the Niagara Canal serving primarily as a back up channel. Traffic through the latter consisted primarily of Class III vessels, and delays constituted a minor portion of the total transit time. Indeed, the locks reached 50 percent

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[1]Previous studies at PTTSC have demonstrated that under a variety of system conditions the SOQA rule leads to a significantly improved waterway operation than a FIFO (First In First Out) rule. For example see (11).

utilizations in 2020 under accelerated growth and only in year 2030 under normal growth.

4. Queuing models, when calibrated, proved quite useful in performing sensitivity analysis, i.e., in testing fluctuations in system parameters. Selected systems, particularly in the Single Welland studies, were shown to be extremely sensitive to the magnitude of lock cycles.

5. The term nominal capacity refers to the maximum theoretical capacity and is determined by the maximum number of vessels that can be locked through in any time period. The occurrence of random arrivals, however, imposes an increasing delay cost as the system approaches nominal capacity. Thus, what is needed is a practical capacity which takes into account this delay function. The definition of practical capacity is to a certain extent arbitrary and is truly a function of a number of factors, each of which may be different for various individuals in various systems under various circumstances. For the purposes of this study, practical capacity was defined as that point when the system reaches 75 percent of its nominal capacity.

6. Nominal capacity of the existing Welland was shown to be 40 lockages per day. Practical capacity as defined above was reached as early as 1990 under accelerated growth and as late as 2010 under normal growth.

7. Nonstructural improvements in the Welland Canal leading to a reduction in lock cycle significantly increased the economic capacity of the system. Given the traffic projections, the capacity of the system was increased by almost a decade under normal growth from that given above.

8. For the Welland Super Locks subsystem, a lock cycle of about 120 minutes as given in the input data was determined to be unreasonably high.

Consequently, a set of canal transit curves for varying lock service rates was developed. The capacity of this system was found to be extremely sensitive to lock service times.

9. All the studies assumed the absence of tandem and multiple lockages. Although these currently constitute only 10-15 percent of the total in the Welland Canal, the relaxation of this assumption could lead to higher lock utilizations than those predicted in the studies.

10. An overall survey of the analysis suggests that nonstructural improvements, particularly those related to lock efficiencies (and smooth channel operation), need to be given more emphasis in light of their impact on system capacity.

B. EVALUATION

Any evaluation of the individual studies and their results as described above must a priori recognize the limitations and assumptions of the studies. The intent of the following presentation is to make the reader aware of these limiting factors so that he may assess the quality and correctness of the studies.

A primary limitation of the study is that it ignores the interaction between system congestion and transport demand. To overcome this limitation, it would be necessary to chart the sensitivity of individual commodity traffic to system performance, in effect forming a feedback loop structure that allows a study of the economics of alternative facilities. Lacking this overall evaluation model, two levels of transport demand were used for each year of future forecast, thus providing what is expected to be the range of actual demand.

The simulations performed in this study are nondynamic in the sense that the nature of system interaction as programmed into the existing

models is not time-dependent. For example, the simulation model does not forecast the future status of the system. Future conditions may be simulated only by forecasting the future values of the simulation inputs, as was done for this study.

A third limitation concerns the precision of results. Given that the main objective of the study was to establish system performance for alternative levels of transport demand, and given the constraints of time and resources available, no further attempt to estimate precise delay values was made.[2] Intermediate simulation results or other means of replication are required to obtain statistically sound delay estimates.[3] Treating these simulation results as precise numerical values is tantamount to ignoring the stochastic features of both the models and the system.

Finally, the simulation results are conditional upon the accuracy of traffic forecast. Transport demand for future years were prepared by NCD under the assumption that both average vessel size and frequency of trips would gradually increase. While this procedure is certainly reasonable, a different assumption or different growth rates would undoubtedly produce different results.

Within the limitations discussed above and in light of the conclusions from the individual subsystem studies, the following evaluation may be expounded.

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[2] In connection with this, one may note that delay values were obtainable only for the Niagara Canal studies.

[3] Note that the simulation methodology provides for a permanent record, so that simulations need not be duplicated.

The most clear-cut result of these studies is that twin-canal configurations are able to provide better service over a longer period of time than the single Welland configurations. The Welland-Niagara subsystems distinctly reflect excess capacity through the end of the current millennium. The benefits in terms of reduced delays and the absence of congestion may have been understated, however, if there exists a potential for significant improvements in lock cycle times.

The single Welland studies provide testimony to the volatile relationship between system capacity and the lock cycles. While the structurally improved Welland (the Welland Super Locks subsystem) affords some relief in the long run under the assumptions of the analysis, it too merits further attention by way of 1) effect of enlarged lock dimensions on trip frequencies and 2) the potential improvement in transit-time through traffic control. Neither of these parameters could be explicitly incorporated into the models and must be either qualitatively assessed or expressed in terms of efficiencies in model input data.

The simulation results presented in this report intimate the need for some additional analysis within the framework of an overall evaluation of the Welland Canal. This analysis should, in particular, verify the accuracy of the simulation data and explore the sensitivity of system performance to incremental changes in facility service rates. These changes in turn may elucidate the implications for fleet and facility designs and for system operation procedures. Given this type of sensitivity analysis, the potential benefits of improvements may be more readily assessed.

REFERENCES

1. Great Lakes Simulation Studies, Volume 1--NETSIM: A General Network Simulator, Report TTSC 7215, Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park, Pennsylvania, 1971.

2. "The Traffic Control System for the Welland Canal," Engineering Journal, June 1968.

3. Luce, A. M., and Sandor, P., "A Systems Approach to the Problem of Increasing the Effective Capacity of the Welland Canal," Transportation Research Forum Proceedings, 1965.

4. Rea, John C., and Nowading, David C., Waterway Systems Simulation: Volume V--Simulation of Multiple Channel Deep Draft Navigation Systems. Report TTSC 7112, Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park, Pennsylvania, 1971.

5. Desai, Kiran J., "Determination of Steady State Conditions for Waterway Simulation Experiments," Tech. Memo. No. 6, Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park, Pennsylvania, June 1972.

6. Rao, Srikanth, "Estimating the Variance of the Sample Mean of Autocorrelated Data in Simulation Experiments," Tech. Memo. No. 7, Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park, Pennsylvania, July 1972.

7. Carroll, Joseph L., and Bronzini, Michael S., Analysis of Waterway Systems--Summary Report, Report TTSC 7212, Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park, Pennsylvania, 1972.

8. Santina, William J., and Wesler, George B., "Duplicate Locks for Illinois Waterway," Journal of the Waterways and Harbors Division, ASCE, Vol. 90, No. WW4, Proc. Paper 4118, Nov., 1964.

9. Davis, J. P., "Tonnage Capacity of Locks," Journal of the Waterways and Harbors Division, ASCE, Vol. 95, No. WW2, Proc. Paper 6577, May, 1969, pp. 201-213.

10. Ferguson, H. A., Engel, H., and Blok, S.I.E., (Untitled), XXII International Navigation Congress, Paris, 1969, Permanent International Association of Navigation Congresses, Brussels, Belgium, Section 1, Inland Navigation, Subject 4, pp. 97-114.

11. Hayward, John, "Simulation Analysis of a Multiple Chamber Lock on the Inland Waterway," Report TTSC 7211, Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park, Pennsylvania, September 1972.

APPENDIX A

SELECTED SIMULATION RESULTS

TABLE A.1. TOTAL CANAL TRANSIT TIME FOR THE EXISTING WELLAND

USING ETT SIMULATION

Year	Size Projections		Average Tonnage Per Transit	Normal Growth		Accelerated Growth	
				Arrival Rate	Average Transit Time	Arrival Rate	Average Transit Time
	Class I	Class II	(Tons)	lockages/day	minutes	lockages/day	minutes
1971	30%	70%	8,980	25.5	754	-	-
1980	23.3	76.7	10,650	26.5	780	27.4	790
1985	19.9	80.1	11,259	27.0	801	28.55	820
1990	16.6	83.6	11,816	27.5	826	29.7	853
1995	14.0	86.0	12,356	28.0	848	31.15	887
2000	11.6	88.4	12,831	28.5	873	32.6	924
2010	9.8	90.2	13,932	29.5	926	35.7	1,005
2020	6.6	93.4	14,918	30.9	990	39.8	1,105
2030	5.3	94.7	16,021	32.3	1,060	44.3	1,217

TABLE A.2. SELECTED SYSTEM PARAMETERS FOR THE WELLAND-FOUR LOCK NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

	Vessel Journeys	Total Transit Time (minutes)	Average Transit Time (minutes)
1980	458	313,715	684.9
1985	470	328,953	699.9
1990	475	333,925	703.4
1995	480	342,528	712.7
2000	491	356,318	725.0
2010	508	381,508	751.5
2020	527	411,060	780.6
2030	554	454,834	821.0

TABLE A.3. SELECTED CANAL PARAMETERS FOR THE WELLAND-FOUR LOCK NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

	Number of Welland Journeys		Average Welland Transit Time (minutes)	Number of Niagara Journeys	Average Niagara Transit Time (minutes)
	Class I	Class II			
1980	113	318	673	27	876
1985	104	325	684	41	869
1990	88	338	682	49	885
1995	83	329	681	68	911
2000	70	325	679	96	918
2010	61	321	677	126	975
2020	51	313	680	163	1,003
2030	39	306	677	209	1,058

TABLE A.4. SELECTED SYSTEM PARAMETERS FOR THE WELLAND-SIX LOCK NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

	Vessel Journeys	Total Transit Time (minutes)	Average Transit Time (minutes)
1980	458	322,234	703.5
1985	470	334,810	712.3
1990	475	341,373	718.6
1995	480	353,968	737.4
2000	491	367,120	747.7
2010	508	393,308	774.2
2020	527	428,411	812.9
2030	554	474,073	855.7

TABLE A.5. SELECTED CANAL PARAMETERS FOR THE WELLAND-SIX LOCK

NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

	Number of Welland Journeys		Average Welland Transit Time (minutes)	Number of Niagara Journeys	Average Niagara Transit Time (minutes)
	Class I	Class II			
1980	112	334	693	12	1,022[a]
1985	103	343	699	24	1,035[b]
1990	89	348	695	38	991
1995	82	331	688	67	999
2000	71	329	693	91	1,020
2010	62	329	695	117	1,039
2020	52	314	692	161	1,081
2030	37	316	693	201	1,138

a, b Not in steady state.

TABLE A.6. SELECTED SYSTEM PARAMETERS FOR THE WELLAND-FIVE LOCK NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

	Vessel Journeys	Total Transit Time (minutes)	Average Transit Time (minutes)
1980	458	314,646	687
1985	470	329,047	700
1990	475	334,875	705
1995	480	343,680	716
2000	489	360,393	737
2010	510	385,050	755
2020	528	419,760	795
2030	555	461,760	832

TABLE A.7. SELECTED CANAL PARAMETERS FOR THE WELLAND-FIVE LOCK

NIAGARA SUBSYSTEM UNDER NORMAL GROWTH

	Number of Welland Journeys		Average Welland Transit Time (minutes)	Number of Niagara Journeys	Average Niagara Transit Time (minutes)
	Class I	Class II			
1980	112	336	680	10	991[a]
1985	99	343	685	28	931
1990	95	342	684	38	945
1995	87	333	680	60	967
2000	71	336	688	82	982
2010	62	335	687	113	994
2020	52	323	689	153	1,055
2030	41	320	685	194	1,105

[a]Not in steady state.

APPENDIX B

DETERMINATION OF EXPECTED TRANSIT TIME (ETT) EQUATIONS

A. Introduction

In the Welland-Niagara studies, where the configuration consists of parallel channels, a channel choice decision rule becomes necessary to distribute traffic between the two branches. The rule will make an unconditional assignment of those ships whose size prohibits them from using one of the channels, otherwise, channel assignment will be made on the basis of least expected transit time. When a vessel arrives at the channel choice point, the simulation model invokes the expected transit time (ETT) equations to execute this rule. The derivation of the ETT equations for the Niagara Canal is accomplished through the "Experience Data Base" (EDB) technique.

Essentially, the EDB procedure involves separating a multichannel system into distinct single channels. Each channel is then simulated individually to determine its unique operating characteristics under various assumptions about traffic levels and traffic composition, and about alternative service facilities and operating rules within the branches. Once a set of observations of channel performance have been recorded, regression analysis is used to relate conditions at the time vessels entered the channel to their subsequent transit times.

The EDB procedure is not used to develop the ETT equation for the Welland Canal, however, because the elaborate control system that currently exists at Welland augers numerous difficulties for simulation. Empirical data is available in the form of daily vessel records and these were obtained from the St. Lawrence Seaway Authority.

B. WELLAND CANAL ETT EQUATIONS

Welland Canal transit data for the month of August, 1971 was used as the basis for this analysis. The format of this data as originally supplied for downstream travel is shown in Table B.1. Data for upstream travel was provided in similar format. Preliminary data treatment consisted of transforming this data into a transit time matrix as shown in Table B.2. This matrix was then subjected to regression analysis with vessel transit time as the dependent variable.

For purposes of regression, it was found necessary to model Welland in the most detailed manner possible. To illustrate, on the macro side, Welland could simply be modeled as one entity, and the independent variables in Table B.2 could only consist of two rows, viz., the number of downbound vessels in the canal and the number of upbound vessels in the canal. Such a model was attempted but the degree of predictability in the resultant regression equation was extremely small. On the micro side, Welland could be modeled as the set of locks, reaches and bridges as it currently exists, and the independent variables could consist of the number of upbound and downbound vessels in each reach and at each upbound and downbound queues of locks and bridges. The data requisite for this model was not available, however. The most detailed model that could be established consisted of a six-entity (reach) representation of Welland with the first and last reaches being the two waiting areas at either ends of the canal. This model is schematically portrayed in Figure 2, p. 18.

The conventional linear model was used in the form:

$$TR_j = a + b_1S_{1j} + b_2S_{2j} + \ldots + b_iS_{ij} + U_j$$

TABLE B.1. REPRESENTATIVE WELLAND TRANSIT DATA DAILY RECORDS

** V E S S E L   T R A N S I T   A N A L Y S I S **

PERIOD ANALYSED : 71/08/01/0001 TO 71/08/31/2359 DOWNBOUND AUG 01 TO AUG 31 1971 09/17/71 PAGE 10

						GROSS	MEAN	TIME OF	.OUTSIDE CANAL.		......INSIDE CANAL / DOWNBOUND......						
AGT	PC #	VESSEL NAME	CL	LNG	BM	TONS	DRAFT	CALL-IN	DOCK	WAIT	DOCK	LOCK7 LOCK1	BRG10 LOCK7	BRG18 BRG10	LOCK8 BRG18	TRANSIT	WAIT+ TRANS
812	7712	CANOPUS	O	619	75	16400	2507	08/21/1110		6 02		6 23	47	2 28	1 18	10 56	16 58
211	7744	NORSE CAPTAIN	O	555	70	14724	2511	08/21/1215		5 47		6 45	1 42	1 56	1 31	11 54	17 41
769	0718	PIC RIVER	I	383	45	3569	1904	08/21/1300	4 00	2 30		6 56	3 02	1 44	1 11	12 53	15 23
181	1346	CAROL LAKE	I	715	75	15265	2404	08/21/1328		7 59		7 32	1 36	2 01	59	12 08	20 07
416	0843	PAUL H TOWNSEND	I	446	50	4302	2201	08/21/1646		6 14		6 27	2 42	1 45	49	11 43	17 57
609	6874	PAUL LORENZ RUSS	O	448	63	4475	1800	08/21/2300		5 31		5 33	1 23	1 42	52	9 30	15 01
INLAND	11					8614			41	[illegible] 32		6 22	1 34	1 49	1 04	10 49	14 21
OCEAN	9					8292			11	5 00	1 07	6 10	1 27	1 50	1 16	10 43	15 43
08/21	20	DOWNBOUND		AVE	GT	8469	TOT GT	169388	28	4 12	30	6 17	1 31	1 50	1 09	10 46	14 58
833	1350	JOHN A FRANCE	I	723	75	15874	2510	08/22/0030		1 13		5 41	2 22	1 52	1 13	11 08	12 21
304	5060	MELTEMI	O	461	61	7986	2508	08/22/0155	1 38	2 28		5 35	59	1 52	50	9 16	11 44
069	5471	DINOS M	O	468	62	7962	1802	08/22/0510		1 32		5 34	1 20	1 54	1 12	10 00	11 32
833	0657	JOHN E F MISENER	I	654	68	12029	2411	08/22/0512		2 22		6 14	1 14	2 01	1 48	11 17	13 39
418	5586	URANUS	O	349	49	2460	1604	08/22/0546		5 49		7 21	1 20	1 57	51	11 29	17 18
127	1765	TADOUSSAC	I	730	75	17948	2509	08/22/0735		2 27		7 55	40	2 08	1 06	11 49	14 16
935	1717	CANADIAN CENTURY	I	730	75	18179	2508	08/22/0842		4 01		5 44	2 26	1 47	1 19	11 16	15 17
935	0770	R BRUCE ANGUS	I	620	68	10760	2108	08/22/0903		5 02		7 51	1 34	2 03	1 20	12 48	17 50
127	0548	STADACONA	I	664	67	11279	2403	08/22/1105		5 23		7 31	2 21	2 05	56	12 53	18 16
409	7650	CAPO SAN MARCO	O	440	59	4999	1505	08/22/1913		3 40		3 48	48	1 45	1 07	7 28	11 08
492	1159	BUCKEYE MONITOR	I	550	58	7377	2011	08/22/1949		3 20		4 57	57	3 13	1 22	10 29	13 49
535	7064	HERMOSA	O	543	69	10217	2510	08/22/1950		4 50		5 08	58	2 30	1 39	10 15	15 05
127	0517	FORT YORK	I	462	56	5915	1510	08/22/2231		3 22		4 31	1 17	2 17	1 49	9 54	13 16
INLAND	8					12420				3 24		6 18	1 36	2 11	1 22	11 27	14 51
OCEAN	5					6724			20	3 40		5 29	1 05	2 00	1 08	9 42	13 21
08/22	13	DOWNBOUND		AVE	GT	10229	TOT GT	132985	08	3 30		5 59	1 24	2 06	1 16	10 46	14 16
954	0908	AVONDALE	I	489	52	4939	1720	08/23/0001		2 02		4 31	1 29	2 02	2 35	10 37	12 39
935	1453	NORTHERN VENTURE CDN	I	730	75	15162	25[illegible]8	08/23/0025		4 16		5 10	1 10	2 14	1 02	9 36	13 52
854	5122	GLOXINIA	O	480	60	7665	2511	08/23/0610		2 00		4 41	1 14	2 05	1 02	9 02	11 02
127	1400	QUETICO	I	730	75	16777	2509	08/23/1040		1 08		5 18	39	2 05	1 03	9 05	10 13
954	1021	WESTDALE	I	569	56	6437	1907	08/23/1042	1 18	2 00		4 25	41	1 47	49	7 42	9 42
713	0924	PATERSON	I	574	59	7857	2001	08/23/1105	2 14	2 41		5 45	1 13	1 37	1 03	9 38	12 19
179	7491	LAWRENTIAN	O	576	75	14807	2510	08/23/1325		1 19		5 52	1 23	1 59	59	10 13	11 32
389	1763	INDUSTRIAL TRANSPORT	I	391	55	4962	2209	08/23/1335		3 30		5 54	45	1 52	48	9 19	12 49
179	7276	PACIFIC SKOU	O	613	75	15761	2509	08/23/1340		4 42		5 29	1 17	1 46	57	9 29	14 11
781	7595	MATIJA GUBEC	O	461	67	9333	2510	08/23/1520		4 17		5 16	1 55	1 33	49	9 33	13 50
486	7737	ACTIVITY	O	447	56	4884	1405	08/23/1921		2 12		6 01	50	1 34	42	9 07	11 19
418	7661	MAHDINA MEEFER	O	342	47	2269	1900	08/23/1934		2 24		6 04	1 25	1 43	34	9 46	12 10
181	0015	MENIHEK LAKE	I	715	75	15150	2400	08/23/2030		2 27		7 03	48	2 05	56	10 52	13 19
127	0525	HOCHELAGA	I	640	67	12068	2307	08/23/2033		3 19		7 13	35	2 16	1 00	11 04	14 23
916	6707	KING MINUS	O	524	65	11157	1530	08/23/2321		2 04		7 21	1 04	1 42	49	10 56	13 00

Source: St. Lawrence Seaway Authority

TABLE B.2 TRANSIT TIME MATRIX FOR ETT ANALYSIS

System conditions and parameters for each vessel at time of channel choice / Vessel Identification Numbers	Vessel 1	Vessel 2	Vessel 3	. . .	Vessel N
# upbound vessels in reach from Lock 1 to Lock 7					
# downbound vessels in reach from Lock 1 to Lock 8					
# upbound vessels in reach from Lock 7 to Bridge 10					
# downbound vessels in reach from Lock 7 to Bridge 10					
# upbound vessels in reach from Bridge 10 to Bridge 18					
# downbound vessels in reach from bridge 10 to Bridge 18					
# upbound vessels in reach from Bridge 18 to Lock 8					
# downbound vessels in reach from Bridge 18 to Lock 8					
# upbound vessels in downstream waiting area					
# downbound vessels in upstream waiting area					
# upbound vessels in dock inside canal					
# downbound vessels in dock insidc canal					

where TR_j and S_{ij} represent the observed transit time and system conditions for vessel j. The symbol U_j represents a random disturbance term. The basic S_{ij} variables are shown in the first column of Table B.2. These were not the only variables, however, since power and logarithmic transformations were also made.

The final results of the regression procedure are shown in Table B.3. Table B.4 provides a description of the variables present in the equations. The fraction of explained variance, R^2, was much higher when the dependent variable, total transit time (TR), did not include the waiting time (see Table B.1, second to last column). Inclusion of waiting time in the dependent variable increased the degree of unpredictability. This may be due to certain features of the existing control system at Welland, features such as vessels called out of the waiting area for tandem lockages, vessel delays due to adverse weather conditions, change of pilot, inspections and other aspects of regulated traffic.

C. NIAGARA CANAL ETT EQUATIONS

EDB simulation runs were executed for four, five and six lock configurations with fleet data generated from 1980, 2000 and 2030 normal growth projections. The output from each run was again transformed into a transit time matrix such as that shown in Table B.2. The matrices for each configuration were merged so as to cover the widest possible range of system conditions and were subjected to regression analysis. The regression models for these Niagara configurations were more detailed than that for Welland, in that the independent variables representing system conditions included not only the reach variables (number of vessels by direction of

TABLE B.3 WELLAND ETT EQUATION (in hours)

(i) UPSTREAM

DEPENDENT VARIABLE: Total transit time through Welland (including wait)

FRACTION OF EXPLAINED VARIANCE: .46733

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LAGNEW	0.376432D 00	0.411421D-01	0.3765927	0.4143
ND_2	0.383365D 00	0.131997D 00	0.1086059	0.1430
SD_3	0.754415D-01	0.427205D-01	0.0644761	0.0875
SD_4	0.926512D-01	0.464242D-01	0.0741416	0.0988
LU_1	0.225923D 00	0.153781D 00	0.0541829	0.0729
LU_W	-0.454765D 00	0.225390D 00	-0.2108705	-0.0999
RU_W	0.256836D 01	0.491750D 00	0.5661076	0.2515
RD_1	-0.324908D 00	0.211833D 00	-0.0573008	-0.0761
LENGTH	0.233132D-02	0.689477D-03	0.1249778	0.1659

INTERCEPT 0.426149D 01

TABLE B.3 Continued

(ii) DOWNSTREAM

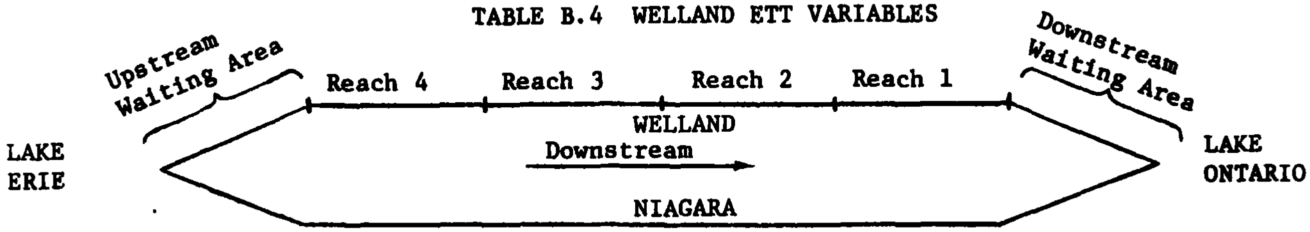
DEPENDENT VARIABLE: Total transit time through Welland (including wait)

FRACTION OF EXPLAINED VARIANCE: .55335

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LAGNEW	0.476575D 00	0.365000D-01	0.4777967	0.5378
ND_4	0.385893D 00	0.119657D 00	0.1111952	0.1556
SU_1	0.184415D-01	0.111713D-01	0.1009804	0.0804
LD_6	-0.389481D 00	0.171599D 00	-0.2016935	-0.1102
RU_1	-0.855268D 00	0.321271D 00	-0.1610076	-0.1290
RD_6	0.208184D 01	0.361084D 00	0.5315529	0.2711
LENGTH	0.367386D-02	0.501665D-03	0.2437868	0.3369

INTERCEPT 0.337656D 01

TABLE B.4 WELLAND ETT VARIABLES



Reach 1 extends from Lock 1 to Lock 7
Reach 2 extends from Lock 7 to Bridge 10
Reach 3 extends from Bridge 10 to Bridge 18
Reach 4 extends from Bridge 18 to Lock 8

Length: vessel length in feet

Lagnew: transit time of the previous vessel

ND_4: number of ships downbound in reach 4

ND_2: number of ships downbound in reach 2

RU_6: square root of number of ships upbound in upstream waiting are

RD_6: square root of number of ships downbound in downstream waiting area

RU_1: square root of number of ships upbound in reach 1

RD_1: square root of number of ships downbound in reach 1

SD_3: square of number of ships downbound in reach 3

SD_4: square of number of ships downbound in reach 4

SU_1: square of number of ships upbound in reach 1

LD_6: $\log_{10}$ of number of ships downbound in downstream waiting area

LU_1: $\log_{10}$ of number of ships upbound in reach 1

LU_6: $\log_{10}$ of number of ships upbound in upstream waiting area

travel) but also the lock variables consisting of the upstream and downstream queue sizes at each individual lock.

The Niagara Canal ETT equations are shown in Tables B.5, B.6 and B.7 for the four, five and six lock configurations respectively. An interpretation of the variables is given in Table B.8 along with schematic diagrams of the relative locations of locks and reaches for each configuration. In general, the equations conform to prior expectations that the transit time of a vessel would be most sensitive to the density of traffic at the nearest lock.

TABLE B.5 FOUR-LOCK NIAGARA ETT EQUATION (in minutes)

(i) UPSTREAM
DEPENDENT VARIABLE: Total Transit Time
FRACTION OF EXPLAINED VARIANCE: 0.97799

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LNQ_1	0.128062D 03	0.147069D 01	0.9216316	0.9708
LNQ_2	0.739400D 02	0.174264D 02	0.0388975	0.1935
LFQ_3	0.505910D 02	0.114121D 02	0.0422043	0.2018
LNQ_4	0.972029D 02	0.138766D 02	0.0551865	0.3096
RSD_1	0.651215D 02	0.229557D 02	0.0217239	0.1307
RSD_2	0.785285D 02	0.350833D 02	0.0158691	0.1035
ROD_2	0.112642D 03	0.321609D 02	0.0243930	0.1607
ROD_3	0.519045D 02	0.209395D 02	0.0203515	0.1144
RSD_5	0.477330D 02	0.159498D 02	0.0215911	0.1378
ROD_5	0.683644D 02	0.176575D 02	0.0294533	0.1771
RSD_6	0.295962D 02	0.114527D 02	0.0181829	0.1192
ROD_6	-0.375666D 02	0.121825D 02	-0.0260663	-0.1419
RSD_7	0.179670D 02	0.488548D 01	0.0311048	0.1685
LENGTH	0.137982D 00	0.576509D-01	0.0166323	0.1105

INTERCEPT 0.673420D 03

TABLE B.5 Continued

(ii) DOWNSTREAM

DEPENDENT VARIABLE: Total Transit Time through Niagara Canal

FRACTION OF EXPLAINED VARIANCE: 0.99289

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LNQ_1	0.944880D 01	0.108216D 01	0.0810104	0.3821
LFQ_2	0.885795D 02	0.662832D 01	0.0619293	0.5347
LNQ_3	0.479479D 02	0.946324D 01	0.0291004	0.2333
LFQ_3	0.646476D 02	0.542014D 01	0.0650312	0.4918
LNQ_4	0.111899D 02	0.692778D 01	0.0078434	0.0763
LFQ_4	0.117500D 03	0.106588D 01	0.8338810	0.9821
RSD_2	0.295368D 02	0.177315D 02	0.0068259	0.0786
ROD_4	0.422856D 02	0.127239D 02	0.0150137	0.1555
RSD_5	0.362803D 02	0.794833D 01	0.0206128	0.2113
ROD_5	0.190467D 02	0.877641D 01	0.0099133	0.1022
RSD_6	0.112175D 03	0.817861D 01	0.0579338	0.5447
ROD_6	-0.141864D 02	0.638055D 01	-0.0119520	-0.1047
RSD_7	0.116941D 03	0.247979D 01	0.2291548	0.9127
ROD_7	-0.163148D 02	0.484939D 01	-0.0177069	-0.1573
LENGTH	0.962425D-01	0.313661D-01	0.0126310	0.1438

INTERCEPT 0.652511D 03

TABLE B.6 FIVE-[illegible]CK NIAGARA ETT EQUATION (in minutes)

(i) UPSTREAM

DEPENDENT VARIABLE: Total Transit Time through Niagara Canal

FRACTION OF EXPLAINED VARIANCE: 0.98590

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LNQ_1	0.131287D 03	0.154000D 01	0.9715041	0.9876
LFQ_1	0.102128D 03	0.304933D 02	0.0370941	0.2397
LNQ_2	0.107556D 03	0.211650D 02	0.0584050	0.3508
LNQ_3	0.432919D 02	0.241377D 02	0.0177532	0.1311
LFQ_3	-0.595863D 02	0.244310D 02	-0.0261788	-0.1770
ROD_1	0.917735D 02	0.204792D 02	0.0399188	0.3137
RSD_2	0.113509D 03	0.361449D 02	0.0296027	0.2255
ROD_2	0.101136D 03	0.351438D 02	0.0257448	0.2075
RSD_3	0.170004D 03	0.267730D 02	0.0696860	0.4240
RSD_7	0.272912D 02	0.124687D 02	0.0195770	0.1593
LENGTH	0.107553D 00	0.593917D-01	0.0161236	0.1323

INTERCEPT 0.101814D 04

TABLE B.6 Continued

(ii) DOWNSTREAM

DEPENDENT VARIABLE: Total Transit Time through Niagara Canal

FRACTION OF EXPLAINED VARIANCE: 0.99609

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LNQ_1	0.426694D 01	0.101592D 01	0.0457397	0.3026
LFQ_2	0.898127D 02	0.119224D 02	0.0675740	0.4948
LNQ_3	0.807327D 02	0.141759D 02	0.0481134	0.3954
LFQ_4	0.630556D 02	0.571296D 01	0.0944388	0.6406
LNQ_5	0.592524D 02	0.799089D 01	0.0469071	0.4889
LFQ_5	0.121777D 03	0.118158D 01	0.8073556	0.9919
ROD_2	0.199838D 02	0.120264D 02	0.0083154	0.1246
RSD_4	0.841145D 02	0.118064D 02	0.0503562	0.4742
ROD_4	0.993720D 02	0.138965D 02	0.0581006	0.4755
RSD_6	0.409592D 02	0.802495D 01	0.0308260	0.3600
ROD_6	0.388190D 02	0.103696D 02	0.0210043	0.2723
RSD_7	0.112125D 03	0.801061D 01	0.0741707	0.7268
RSD_8	0.122381D 03	0.265781D 01	0.3091608	0.9611
ROD_8	0.967826D 01	0.411984D 01	0.0153297	0.1748
LENGTH	0.627421D-01	0.250447D-01	0.0124431	0.1861

INTERCEPT 0.748405D 03

TABLE B.7 SIX-LOCK NIAGARA ETT EQUATION (in minutes)

(i) UPSTREAM

DEPENDENT VARIABLE: Total Transit Time through Niagara Canal

FRACTION OF EXPLAINED VARIANCE: 0.96375

VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LNQ_1	0.115567D 03	0.202687D 02	0.5001696	0.8023
LNQ_6	-0.845838D 02	0.299256D 02	-0.1650713	-0.5544
LFQ_6	0.336228D 02	0.2019000 02	0.1960829	0.3654
RSD_1	0.185674D 03	0.331979D 02	0.2852926	0.7957
RSD_2	0.239012D 03	0.569587D 02	0.2227606	0.7032
ROD_2	-0.146597D 03	0.906919D 02	-0.0818607	-0.3560
RSD_7	0.904977D 02	0.439171D 02	0.1274145	0.4369
ROD_8	0.847158D 02	0.195474D 02	0.2215236	0.7145
RSD_9	0.605419D 02	0.202067D 02	0.2194666	0.5769
ROD_9	0.500531D 02	0.904412D 01	0.3026941	0.7936

INTERCEPT 0.941233D 03

TABLE B.7 Continued

(ii) DOWNSTREAM

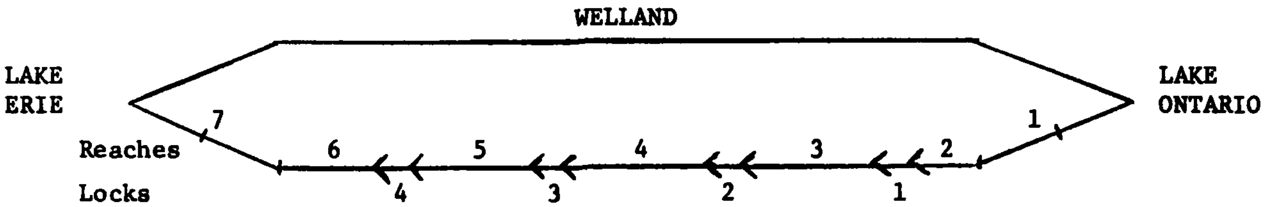
DEPENDENT VARIABLE: Total Transit Time through Niagara Canal

FRACTION OF EXPLAINED VARIANCE: 0.86970

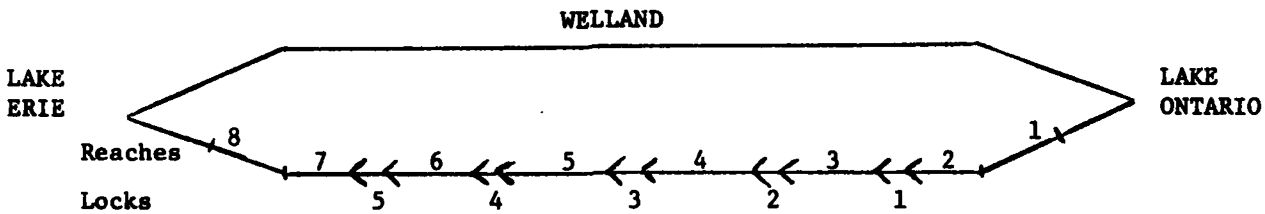
VARIABLE	REGRESSION COEFFICIENT	STAND. DEVIATION FOR COEFFICIENT	STAND. REGRESSION COEFFICIENT	PARTIAL CORRELATION COEFFICIENT
LFQ_1	-0.263485D 03	0.197382D 02	-1.2177836	-0.9121
LNQ_2	0.698844D 03	0.145431D 03	0.3417007	0.6251
LFQ_6	0.686898D 03	0.158272D 03	0.3750146	0.5861
RSD_1	-0.206870D 03	0.109104D 03	-0.1341303	-0.3013
ROD_1	-0.696366D 03	0.163901D 03	-0.3025588	-0.5779
RSD_2	-0.691331D 03	0.163259D 03	-0.2846443	-0.5766
ROD_5	-0.436546D 03	0.244021D 03	-0.1235550	-0.2857
RSD_9	0.308975D 03	0.772103D 02	0.3130363	0.5549
ROD_9	0.950879D 02	0.299316D 02	0.2310617	0.4679

INTERCEPT 0.121421D 04

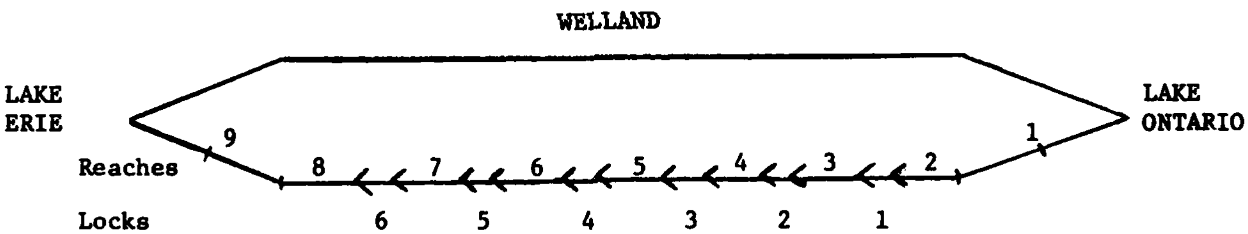
TABLE B.8 NIAGARA ETT VARIABLES



(i) Four-lock configuration (with seven reaches)



(ii) Five-lock configuration (with eight reaches)



(iii) Six-lock configuration (with nine reaches)

LNQ_i = number of vessels in near[1] queue at lock i

LFQ_i = number of vessels in far queue at Lock i

RSD_j = number of vessels travelling same direction[2] in Reach j

ROD_j = number of vessels travelling opposite direction in Reach j

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[1] in relation to the subject vessel

[2] in relation to the subject vessel's direction of travel

APPENDIX C

DESCRIPTION OF THE QUEUING MODEL

USED IN THE SINGLE WELLAND STUDIES

The queuing model used to supplement the Single Welland Simulation Studies (see Section IV) is a simple waiting-line model, mathematically categorized as M/G/1. That is, arrivals into the service facility are assumed to be Poisson distributed, there is only one service facility and the service times for the arrival units are independent with some common probability distribution whose mean $1/\mu$ and variance σ^2 are known.

The terminology used below is as follows:

λ = mean arrival rate (expected number of arrivals per minute)

μ = mean service rate (expected number of units completing service per minute)

σ^2 = variance of the service distribution

$\rho = \lambda/\mu$ = traffic intensity

W = waiting time in queue in minutes

Under the assumptions given above, the Pollaczek-Khintchine formula establishes the waiting time[1] as:

$$W = \frac{\lambda^2\sigma^2 + \rho^2}{2\lambda\ (1-\rho)}$$

In the context of this analytical model, the Welland Canal is viewed as one entity--a single service facility. Arrival units incur delays in waiting areas at either ends outside the Welland Canal and the transit time through the canal itself is fairly constant. This approach was formulated on the basis of the empirical data as given below. The transit time distribution through the Welland Canal has a very small variance while the delay distributions have large variances.

Although a state-dependent function for Welland Canal transit time was obtained through regression (i.e., the transit time through the canal

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[1]Note: when the service distribution is exponential, so that $\sigma^2 = 1/\mu^2$, then the above equation reduces to the M/M/1 case with $W = \frac{\lambda}{\mu(\mu - \lambda)}$

Transit Time Distribution	Upstream Waiting Area	Welland Canal	Downstream Waiting Area
Mean (min.)	151.00	615.00	149.00
Standard Deviation (min.)	122.00	131.00	102.00
St. Dev. as % of the Mean	80.79%	21.30%	68.45%

Source: VESSEL TRANSIT ANALYSIS, St. Lawrence Seaway Authority.

was expressed as a function of the system conditions), the major contribution to the magnitude of transit time was the intercept term with other variables providing for minor fluctuations indicating again that once a ship enters the canal, its actual transit time is almost constant.

The primary objective of this effort then became the prediction of delays in waiting areas outside the canal. The rate at which the canal could absorb the arrival flows and dissipate queues needed to be identified. This rate, or more accurately this service distribution was determined through analysis of the VESSEL TRANSIT ANALYSIS daily reports for the months of June and August.

The traffic flows for these months are shown in Figure C.1. Weekly patterns may be readily seen, although there are enough variations to make accurate prediction difficult. Average flows were 25.1 and 24.7 per day discounting multiple lockages.[2] Since the number of daily arrivals vary greatly from day to day, the delay times for these units were associated with the traffic density into the canal during the 24 hours preceding an arrival.

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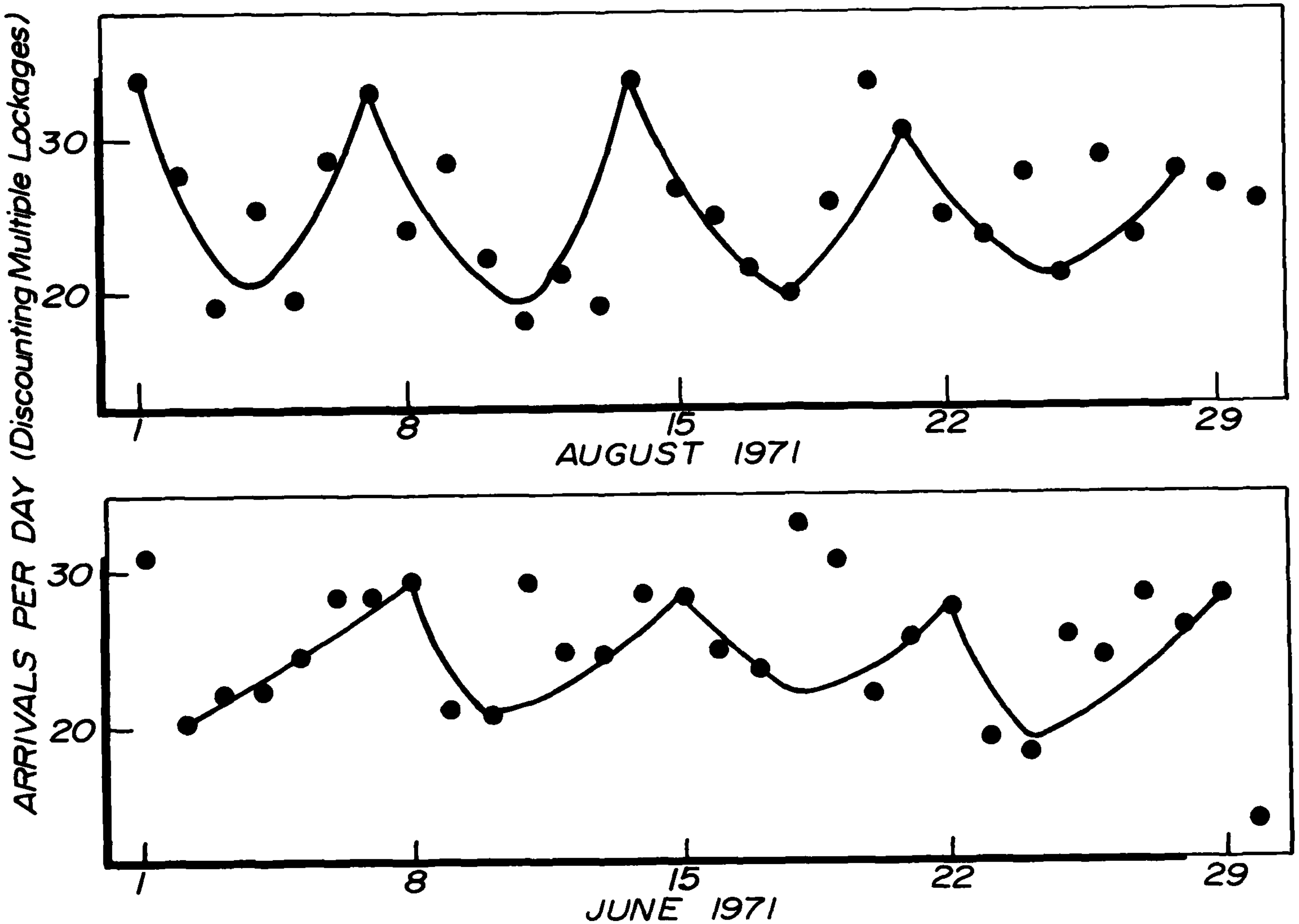
[2] Approximately 11% of the arrival units were assumed to undergo multiple lockages.



Source: VESSEL TRANSIT ANALYSIS, St. Lawrence Seaway Authority

Figure C.1. Traffic Flows at the Welland Canal

The results from this analysis are shown in Figure C.2. The service distribution finally obtained is described in terms of an average service cycle[3], μ equal to .0112 min^{-1} ($1/\mu \sim 90$ min.) and a standard deviation, σ equal to .0288 min^{-1}. The waiting time characterized by these parameters corresponds well with empirical data over a wide range of traffic.

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[3]A service cycle is the time to process two vessels from opposite directions consecutively.

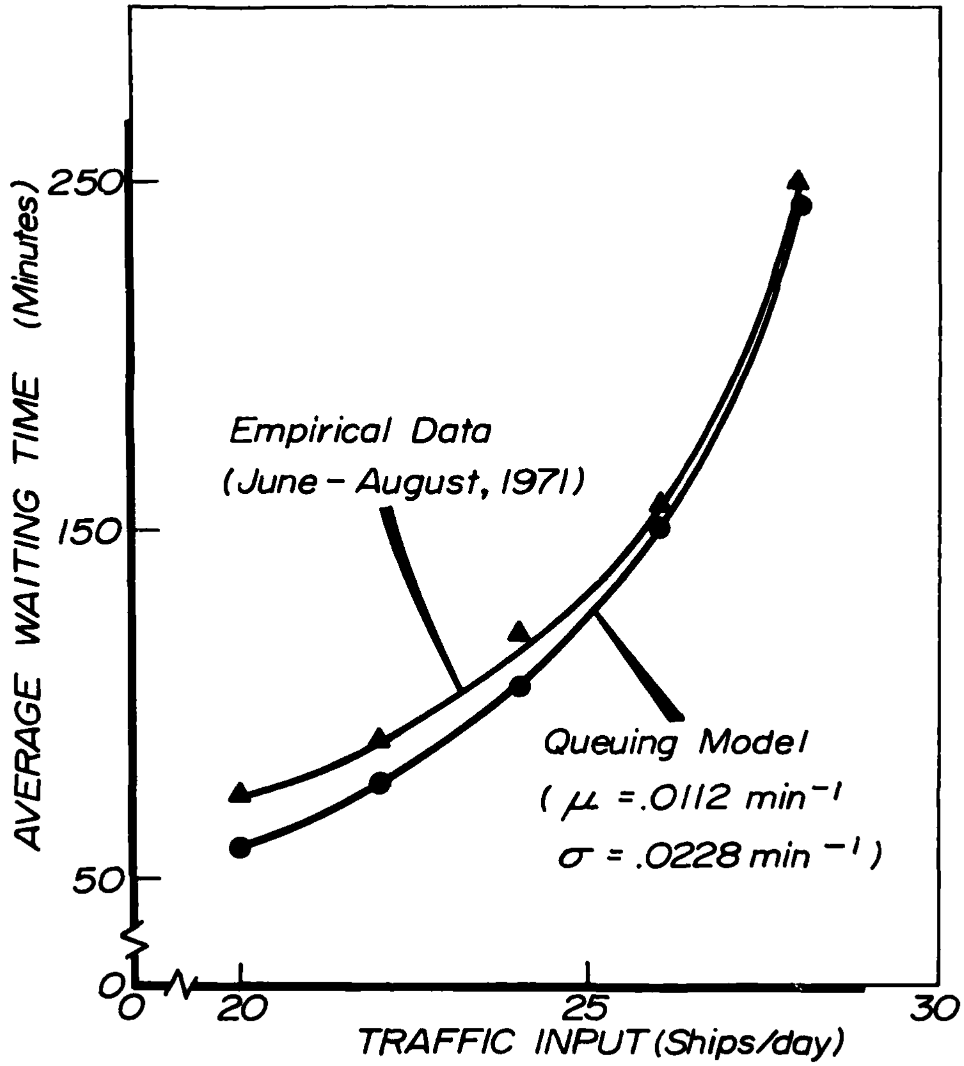
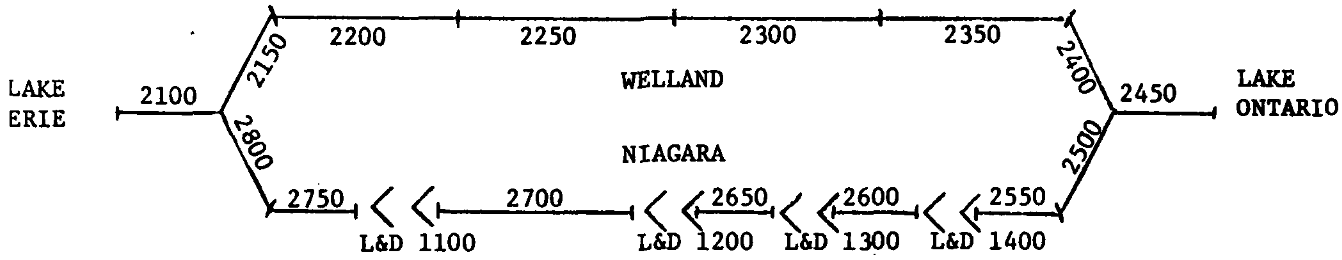


Figure C.2. Comparison of Analytical Results with Empirical Data

APPENDIX D

INPUT DATA

TABLE D.1. WELLAND-FOUR LOCK NIAGARA SUBSYSTEM



1. Reach Data for Niagara Canal

Reach Identification Number	Length (miles)	Mean Transit Time (minutes)	Standard Deviation
2500	8.1	29	Based on an analysis of the reach between the Eisenhower & Snell locks, the standard deviation was set equal to 25% of the mean. A normal distribution was used.
2550	1.5	10	
2600	4.1	82	
2650	1.2	24	
2700	18.8	121	
2750	4.0	40	
2800	62.7	221	

2. Reaches 2100 and 2450 are dummy reaches for simulation purposes only.

3. Transit times through the Welland reaches were determined from the system conditions during simulation by way of the ETT equations.

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GREAT LAKES SIMULATION STUDIES. VOLUME 2. LAKE ERIE-LAKE ONTARI--ETC(U)
NOV 72 J L CARROLL, S RAO DACW23-72-C-0066

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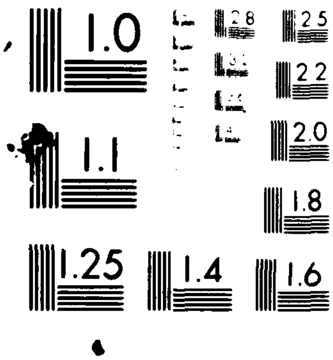
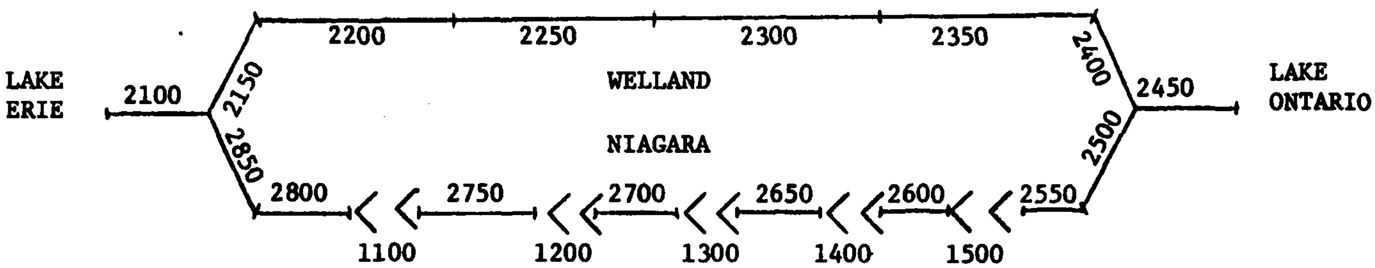


MICROCOPY RESOLUTION TEST CHART

TABLE D.2. WELLAND-FIVE LOCK NIAGARA SUBSYSTEM



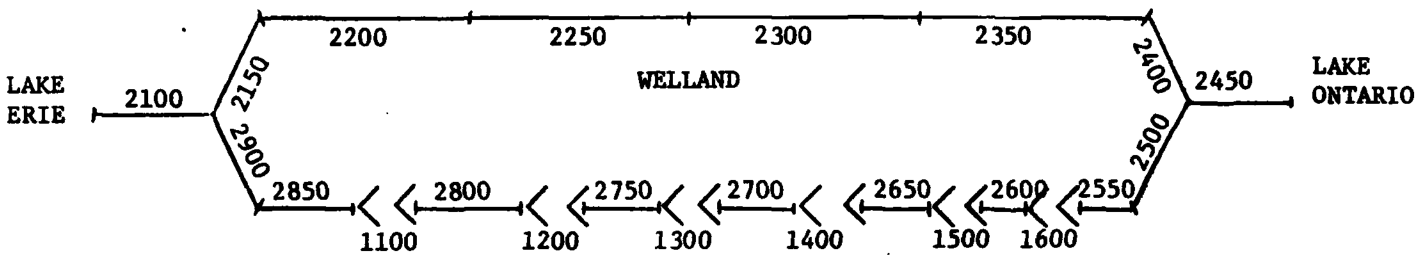
1. Reach Data For Niagara Canal

Reach ID Number	Length (miles)	Mean Transit Time (minutes)	Standard Deviation
2500	8.1	29	
2550	1.5	10	Set to 25% of the mean with a normal distribution.
2600	1.7	34	
2650	2.1	43	
2700	.4	8	
2750	18.8	121	
2800	4.0	40	
2850	62.7	221	

2. Reaches 2100 and 2450 are dummy reaches for simulation purposes only.

3. Transit times through the Welland reaches were determined from the system conditions during simulation by way of the ETT equation.

TABLE D.3. WELLAND-SIX LOCK NIAGARA SUBSYSTEM



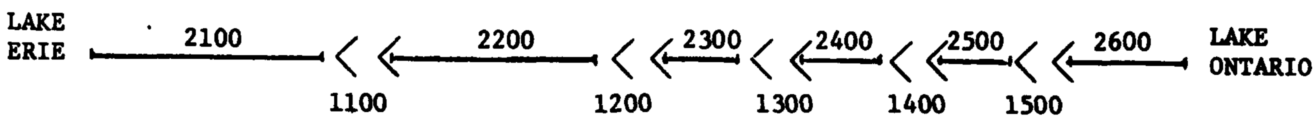
1. Reach Data For Niagara Canal

Reach ID Number	Length (miles)	Mean Transit Time (minutes)	Standard Deviation
2500	8.1	29	
2550	1.2	8	
2600	1.8	36	Set to 25% of the mean with a normal distribution.
2650	0.4	8	
2700	0.7	10	
2750	0.4	8	
2800	18.7	121	
2850	4.0	40	
2900	62.7	221	

2. Reaches 2100 and 2450 are dummy reaches for simulation purposes only.

3. Transit times through the Welland reaches were determined from the system conditions during simulation by way of the ETT equations.

TABLE D.4. WELLAND SUPERLOCKS SUBSYSTEM



Reach ID Number	Length (miles)	Mean Transit Time (minutes)	Standard Deviation
2100	66.7	261	
2200	18.8	121	Set to 25% of the mean with a normal distribution.
2300	.4	8	
2400	2.1	43	
2500	1.7	34	
2600	9.6	39	

Tables D.5 through D.12 summarize fleet and lock data observed at Poe Lock (Sault Ste Marie) during the period May - July 1972.

TABLE D.5. FREQUENCY DISTRIBUTION OF LOCKAGE TIMES - ALL VESSELS

LOCKAGE TYPE	0-8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	60+	AVERAGE
APPRO UP	0	0	0	2	2	5	12	20	24	18	27	16	15	10	9	7	3	6	3	1	1	0	1	0	0	0	0	5	29
PERCENT	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.11	0.13	0.10	0.14	0.09	0.08	0.05	0.05	0.04	0.02	0.03	0.02	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.03	
APPRO DN	0	0	0	0	0	0	0	0	0	7	16	15	21	13	22	21	24	17	9	12	5	5	4	1	4	0	2	18	35
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.07	0.10	0.06	0.10	0.10	0.11	0.08	0.04	0.06	0.02	0.02	0.02	0.00	0.02	0.00	0.01	0.08	
ENTRY UP	4	17	34	29	31	19	6	7	3	2	4	2	5	2	1	1	2	2	1	0	2	0	1	0	1	2	0	9	20
PERCENT	0.02	0.09	0.18	0.15	0.17	0.10	0.03	0.04	0.02	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.05	
ENTRY DN	0	0	0	0	2	0	4	5	14	18	18	14	18	16	11	13	16	5	10	2	5	4	5	2	3	2	0	29	32
PERCENT	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.02	0.06	0.08	0.08	0.06	0.08	0.07	0.05	0.06	0.07	0.02	0.05	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.00	0.13	
LCKAG UP	1	0	0	0	0	1	0	4	24	49	31	34	9	11	6	5	1	2	1	2	0	0	2	0	0	0	0	4	30
PERCENT	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.13	0.26	0.17	0.18	0.05	0.06	0.03	0.03	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02	
LCKAG DN	0	0	0	0	0	0	0	5	14	42	38	48	16	20	6	4	4	3	3	2	2	4	0	2	2	0	0	1	30
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.19	0.18	0.22	0.07	0.09	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.00	0.01	0.01	0.00	0.00	0.00	
EXIT UP	29	56	50	25	14	4	4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4	11
PERCENT	0.16	0.30	0.27	0.13	0.07	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	
EXIT DN	156	43	10	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	8
PERCENT	0.72	0.20	0.05	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

TABLE D.6. FREQUENCY DISTRIBUTION OF LOCKAGE TIMES - VESSEL LENGTH 1'-399'

LOCKAGE TYPE	0-8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	60+	AVERAGE
APPRO UP	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
APPRO DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
ENTRY UP	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	19
PERCENT	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	
ENTRY DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
LCKAG UP	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
LCKAG DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
EXIT UP	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
PERCENT	0.00	0.00	0.67	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
EXIT DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

TABLE D.7. FREQUENCY DISTRIBUTION OF LOCKAGE TIMES - VESSEL LENGTH 400'-599'

LOCKAGE TYPE	0-8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	60+	AVERAGE
APPRO UP	0	0	0	1	0	1	10	15	15	13	18	5	8	4	6	5	1	4	3	1	0	0	1	0	0	0	0	3	29
PERCENT	0.00	0.00	0.00	0.01	0.00	0.01	0.09	0.13	0.13	0.11	0.16	0.04	0.07	0.04	0.05	0.04	0.01	0.04	0.03	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03	
APPRO DN	0	0	0	0	0	0	0	0	0	4	8	9	14	9	15	14	10	7	3	9	1	2	3	0	2	0	1	10	37
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.07	0.12	0.07	0.12	0.12	0.08	0.06	0.02	0.07	0.01	0.02	0.02	0.00	0.02	0.00	0.01	0.08	
ENTRY UP	3	10	24	18	17	9	4	5	3	2	3	1	4	1	1	0	1	1	0	0	1	0	1	0	0	1	0	4	19
PERCENT	0.03	0.09	0.21	0.16	0.15	0.08	0.04	0.04	0.03	0.02	0.03	0.01	0.04	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.04	
ENTRY DN	0	0	0	0	0	0	3	3	9	10	13	7	14	10	4	4	3	1	9	1	3	3	2	2	1	2	0	17	33
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.07	0.08	0.11	0.06	0.12	0.08	0.03	0.03	0.02	0.01	0.07	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.00	0.14	
LCKAG UP	0	0	0	0	0	1	0	4	17	32	21	22	4	5	2	3	0	0	1	0	0	0	0	0	0	0	0	2	29
PERCENT	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.04	0.15	0.28	0.18	0.19	0.04	0.04	0.02	0.03	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	
LCKAG DN	0	0	0	0	0	0	0	4	10	27	29	29	4	7	3	2	2	2	2	0	0	0	0	0	0	0	0	0	28
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.22	0.24	0.24	0.03	0.06	0.02	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
EXIT UP	19	36	30	14	10	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	12
PERCENT	0.17	0.32	0.26	0.12	0.09	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	
EXIT DN	99	13	4	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	7
PERCENT	0.82	0.11	0.03	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	

TABLE D.8. FREQUENCY DISTRIBUTION OF LOCKAGE TIMES - VESSEL LENGTH 500'-730'

LOCKAGE TYPE	0-8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	60+	AVERAGE
APPRO UP	0	0	0	1	2	4	2	4	5	5	8	7	5	4	2	2	2	2	0	0	1	0	0	0	0	0	0	1	28
PERCENT	0.00	0.00	0.00	0.02	0.04	0.07	0.04	0.07	0.09	0.09	0.14	0.12	0.09	0.07	0.04	0.04	0.04	0.04	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	
APPRO DN	0	0	0	0	0	0	0	0	0	3	8	6	7	3	5	5	9	7	4	3	4	2	1	1	2	0	1	8	38
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.10	0.08	0.09	0.04	0.06	0.06	0.11	0.09	0.05	0.04	0.05	0.03	0.01	0.01	0.03	0.00	0.01	0.10	
ENTRY UP	1	6	9	9	13	8	0	1	0	0	1	1	0	0	0	1	1	1	1	0	1	0	0	0	1	0	0	2	19
PERCENT	0.02	0.11	0.16	0.16	0.23	0.14	0.00	0.02	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.04	
ENTRY DN	0	0	0	0	2	0	1	2	5	8	5	6	3	5	4	8	9	3	0	1	1	1	2	0	2	0	0	11	35
PERCENT	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.03	0.06	0.10	0.06	0.08	0.04	0.06	0.05	0.10	0.11	0.04	0.00	0.01	0.01	0.01	0.03	0.00	0.03	0.00	0.00	0.14	
LCKAG UP	1	0	0	0	0	0	0	0	6	15	10	9	5	5	4	0	1	0	0	0	0	0	0	0	0	0	0	0	27
PERCENT	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.25	0.18	0.16	0.09	0.09	0.07	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
LCKAG DN	0	0	0	0	0	0	0	1	4	15	9	19	11	11	1	1	2	1	1	1	0	2	0	0	0	0	0	0	30
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.19	0.11	0.24	0.14	0.14	0.01	0.01	0.03	0.01	0.01	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	
EXIT UP	10	19	15	8	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	11
PERCENT	0.18	0.33	0.26	0.14	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	
EXIT DN	57	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8
PERCENT	0.72	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	

TABLE D.9. FREQUENCY DISTRIBUTION OF LOCKAGE TIMES - VESSEL LENGTH 731'-949'

LOCKAGE TYPE	0-5	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	60+	AVERAGE
APPRO UP	0	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26
PERCENT	0.00	.00	.00	.00	.00	.00	.00	.25	.25	.00	.25	.00	.00	.25	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	
APPRO DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	1	1	0	0	0	0	0	0	0	0	0	39
PERCENT	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.29	.00	.43	.14	.14	.00	.00	.00	.00	.00	.00	.00	.00	.00	
ENTRY UP	0	0	1	1	1	0	0	0	[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	19
PERCENT	0.00	.00	.25	.25	.25	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.25	
ENTRY DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	1	0	0	1	0	0	0	0	0	0	0	40
PERCENT	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.14	.14	.43	.14	.00	.00	.14	.00	.00	.00	.00	.00	.00	.00	
LCKAG UP	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	[illegible]	0	0	0	0	0	0	0	0	0	0	0	1	36
PERCENT	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.50	.00	.25	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.25	
LCKAG DN	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	1	0	0	0	0	0	0	0	0	1	0	0	0	37
PERCENT	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.14	.29	.29	.14	.00	.00	.00	.00	.00	.00	.00	.00	.14	.00	.00	.00	
EXIT UP	0	0	1	1	0	1	[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16
PERCENT	0.00	.00	.25	.25	.00	.25	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.25	
EXIT DN	0	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
PERCENT	0.00	.71	.29	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	

TABLE D.10. FREQUENCY DISTRIBUTION OF LOCKAGE TIMES - VESSEL LENGTH 950'-1150'

LOCKAGE TYPE	0-8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	60+	AVERAGE
APPRO UP	0	0	0	0	0	0	0	0	1	0	0	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	31
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.33	0.22	0.11	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	
APPRO DN	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	2	1	0	0	1	0	0	0	0	0	0	40
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.22	0.22	0.22	0.11	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	
ENTRY UP	0	1	0	1	0	1	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	31
PERCENT	0.00	0.11	0.00	0.11	0.00	0.11	0.11	0.11	0.00	0.00	0.00	0.00	0.11	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.11	
ENTRY DN	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	0	1	0	1	0	0	0	1	0	0	0	0	1	40
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.11	0.22	0.00	0.11	0.00	0.11	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.11	
LCKAG UP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	2	0	0	2	0	0	0	0	1	46
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.22	0.00	0.22	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.11	
LCKAG DN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	0	2	1	0	0	1	51
PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.22	0.22	0.00	0.22	0.11	0.00	0.00	0.11	
EXIT UP	0	1	2	1	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
PERCENT	0.00	0.11	0.22	0.11	0.33	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
EXIT DN	0	4	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
PERCENT	0.00	0.44	0.44	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

TABLE D.11. VESSEL TRANSIT BY LENGTH OF VESSEL

CL. 1 VES	3	0.007
CL. 2 VES	235	0.583
CL. 3 VES	136	0.337
CL. 4 VES	11	0.027
CL. 5 VES	18	0.045
TOTAL	403	1.000

TABLE D.12. AVERAGE TONS PER LOADED VESSEL BY COMMODITY

VESSEL CLASS	TONS PER LOADED VESSEL						
	GRAIN	COAL	PETROLEUM	CEMENT	IRON ORE	CHEM	MISC
CL.1 VES	0.	0.	9019.	5400.	0.	0.	4300.
CL.2 VES	14636.	12895.	7587.	13155.	20095.	0.	10000.
CL.3 VES	26049.	21089.	0.	0.	27238.	0.	0.
CL.4 VES	0.	0.	0.	0.	39185.	0.	0.
CL.5 VES	0.	0.	0.	0.	57617.	0.	0.

Tables D.13 through D.17 contain fleet data.

TABLE D.13. FLEET COMPOSITION OF VESSEL TRANSITS

		Percentage Distribution by Vessel Class						
	Vessel Class	1970	1980	1990	2000	2010	2020	2030
No.	Length							
1	1- 399	30.0	23.3	16.4	11.6	9.8	6.6	5.3
2	400- 599	42.0	38.7	34.6	29.5	23.4	17.2	11.6
3	600- 730	28.0	36.0	39.8	42.9	45.6	47.8	48.4
4	731- 949	-	1.4	5.2	8.6	12.8	17.3	22.1
5	950-1150	-	0.6	3.8	7.4	9.4	11.1	12.6
	Total Fleet	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE D.14. LAKE ERIE-LAKE ONTARIO TRAFFIC UNDER ACCELERATED GROWTH[a]

Commodity	1970			1980			1990			2000			2010			2020			2030		
	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down
	(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)		
Iron Ore	16,091	12,525	3,566	19,682	15,344	4,338	24,324	18,919	5,405	30,347	23,565	6,782	38,206	29,716	8,490	48,110	37,509	10,601	60,707	47,238	13,469
Stone	982	949	33	1,124	1,044	80	1,255	1,255	-	1,494	1,494	-	1,780	1,780	-	2,120	2,120	-	2,342	2,342	-
Coal	10,714	-	10,714	12,853	-	12,853	15,541	-	15,541	17,128	-	17,128	19,308	-	19,308	21,201	-	21,201	23,424	-	23,424
Petroleum	1,802	1,368	434	2,330	1,848	482	3,089	2,413	676	4,138	3,334	804	5,341	4,382	959	7,339	6,034	1,305	9,760	8,198	1,562
General Cargo	8,200	5,600	2,600	10,845	6,507	4,338	13,127	7,915	5,212	15,404	9,196	6,208	18,213	10,955	7,258	21,201	12,721	8,480	25,181	15,226	9,955
Grain	19,950	-	19,950	26,751	-	26,751	31,177	-	31,177	37,015	-	37,015	42,998	-	42,998	50,066	-	50,066	58,365	-	58,365
Subtotal	57,739	20,442	37,297	73,585	24,743	48,842	88,513	30,502	58,011	105526	37,589	67,937	125846	46,833	79,013	150037	58,384	91,653	179779	73,004	106775
Other	5,130	701	4,429	6,748	883	5,865	8,012	1,062	6,950	9,426	1,379	8,047	11,092	1,643	9,449	13,047	1,957	11,090	15,421	2,538	12,883
Total	62,869	21,143	41,726	80,333	25,626	54,707	96,525	31,564	64,961	114952	38,968	75,984	136938	48,476	88,462	163084	60,341	102743	195200	75,542	119658
Avg. tonnage per transit	8,980			10,650			11,816			12,831			13,922			14,918			16,021		

[a]1970 data are actual, others are projected.

TABLE D.15. LAKE ERIE-LAKE ONTARIO VESSEL TRANSITS UNDER ACCELERATED GROWTH[a]

Month		1970	1980	1990	2000	2010	2020	2030
April	Total	535	576	623	683	749	832	927
	Up	315	339	367	402	441	490	546
	Down	220	237	256	281	308	342	381
May	Total	920	991	1,074	1,178	1,293	1,439	1,604
	Up	441	475	515	565	620	690	769
	Down	479	516	559	613	673	749	835
June	Total	799	861	932	1,022	1,121	1,247	1,389
	Up	405	436	472	518	568	632	704
	Down	394	425	460	504	553	615	685
July	Total	842	907	982	1,077	1,182	1,315	1,466
	Up	425	458	496	544	597	664	740
	Down	417	449	486	533	585	651	726
August	Total	831	896	971	1,065	1,169	1,300	1,449
	Up	408	440	477	523	574	638	711
	Down	423	456	494	542	595	662	738
September	Total	851	917	994	1,091	1,197	1,331	1,483
	Up	430	463	502	551	605	673	750
	Down	421	454	492	540	592	658	733
October	Total	904	974	1,055	1,157	1,269	1,412	1,574
	Up	462	498	539	591	648	721	804
	Down	442	476	516	566	621	691	770

TABLE D.15. CONTINUED

Month		1970	1980	1990	2000	2010	2020	2030
November	Total	863	930	1,007	1,104	1,211	1,347	1,502
	Up	418	450	487	534	586	652	727
	Down	445	480	520	570	625	695	775
December	Total	456	491	531	582	638	709	790
	Up	187	201	217	238	261	290	323
	Down	269	290	314	344	377	419	467
Yearly	Total	7,001	7,543	8,169	8,959	9,829	10,932	12,184
	Up	3,491	3,760	4,072	4,466	4,900	5,450	6,074
	Down	3,510	3,783	4,097	4,493	4,929	5,482	6,110
Avg. Daily		25.5	27.4	29.7	32.6	35.7	39.8	44.3
Avg. Monthly		777.9	838.1	907.7	995.4	1,092.1	1,214.7	1,353.8

[a] 1970 data are actual, others are projected.

TABLE D.16. LAKE ERIE-LAKE ONTARIO TRAFFIC UNDER NORMAL GROWTH[a]

Commodity	1970			1980			1990			2000			2010			2020			2030		
	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down	Total	Up	Down
	(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)			(1,000 tons)		
Iron Ore	16,091	12,525	3,566	18,988	14,780	4,208	22,527	17,535	4,992	26,550	20,666	5,884	31,538	24,549	6,989	37,331	29,058	8,273	44,089	34,318	9,771
Stone	982	949	33	1,080	1,044	36	1,198	1,158	40	1,326	1,281	45	1,463	1,414	49	1,610	1,556	54	1,767	1,708	59
Coal	10,714	-	10,714	12,428	-	12,428	14,357	-	14,357	15,000	-	15,000	16,000	-	16,000	16,500	-	16,500	17,000	-	17,000
Petroleum	1,802	1,368	434	2,254	1,751	503	2,826	2,244	582	3,550	2,873	677	4,452	3,666	786	5,617	4,706	911	7,078	6,019	1,059
General Cargo	8,200	5,600	2,600	10,500	6,300	4,200	12,100	7,300	4,800	13,500	8,100	5,400	15,000	9,000	6,000	16,500	9,900	6,600	18,300	11,000	7,300
Grain	19,950	-	19,950	25,800	-	25,800	28,900	-	28,900	32,400	-	32,400	35,500	-	35,500	38,900	-	38,900	42,400	-	42,400
Subtotal	57,739	20,442	37,297	71,050	23,875	47,175	81,908	28,237	53,671	92,326	32,920	59,406	103953	38,629	65,324	116458	45,220	71,238	130634	53,045	77,589
Other	5,130	701	4,429	6,497	836	5,661	7,429	988	6,441	8,281	1,152	7,129	9,191	1,352	7,839	10,132	1,583	8,549	11,163	1,857	9,311
Total	62,869	21,143	41,726	77,547	24,711	52,836	89,337	29,225	60,112	100607	34,072	66,535	113144	39,981	73,163	126590	46,803	79,787	141802	54,902	86,900
Avg. tonnage per transit	8,980			10,650			11,816			12,831			13,932			14,918			16,021		

[a]1970 data are actual, others are projected.

TABLE D.17. LAKE ERIE-LAKE ONTARIO VESSEL TRANSITS UNDER NORMAL GROWTH[a]

Month		1970	1980	1990	2000	2010	2020	2030
April	Total	535	556	577	598	619	646	673
	Up	315	327	339	351	363	379	395
	Down	220	229	238	247	256	267	278
May	Total	920	957	994	1,031	1,068	1,116	1,164
	Up	441	459	477	495	513	536	559
	Down	479	498	517	536	555	580	605
June	Total	799	831	863	895	927	969	1,011
	Up	405	421	437	453	469	490	511
	Down	394	410	426	442	458	479	500
July	Total	842	876	910	944	978	1,022	1,066
	Up	425	442	459	476	493	515	537
	Down	417	434	451	468	485	507	529
August	Total	831	864	897	930	963	1,006	1,049
	Up	408	424	440	456	472	493	514
	Down	423	440	457	474	491	513	535
September	Total	851	885	919	953	987	1,032	1,077
	Up	430	447	464	481	498	521	544
	Down	421	438	455	472	489	511	533
October	Total	904	940	976	1,012	1,048	1,095	1,142
	Up	462	480	498	516	534	558	582
	Down	442	460	478	496	514	537	560

TABLE D.17. CONTINUED

Month		1970	1980	1990	2000	2010	2020	2030
November	Total	863	898	933	968	1,003	1,049	1,095
	Up	418	435	452	469	486	508	530
	Down	445	463	481	499	517	541	565
December	Total	456	474	492	510	528	551	574
	Up	187	194	201	208	215	224	233
	Down	269	280	291	302	313	327	341
Yearly	Total	7,001	7,281	7,561	7,841	8,121	8,486	8,851
	Up	3,491	3,629	3,767	3,905	4,043	4,224	4,405
	Down	3,510	3,652	3,794	3,936	4,078	4,262	4,446
Avg. Daily		25.5	26.5	27.5	28.5	29.5	30.9	32.2
Avg. Monthly		777.9	809.0	840.1	871.2	902.3	942.9	983.4

[a] 1970 data are actual, others are projected.

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